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Sanders et al.

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[45] **Date of Patent:** **Jun. 15, 1999**

- [54] **HIGH POWER PUMPED MID-IR WAVELENGTH SYSTEMS USING NONLINEAR FREQUENCY MIXING (NFM) DEVICES**
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- [73] Assignee: **SDL, Inc.**, San Jose, Calif.
- [21] Appl. No.: **08/649,560**
- [22] Filed: **May 17, 1996**
- [51] **Int. Cl.⁶** **H01S 3/10**
- [52] **U.S. Cl.** **372/22; 359/326**
- [58] **Field of Search** **359/326, 330; 372/20, 21, 22, 37**

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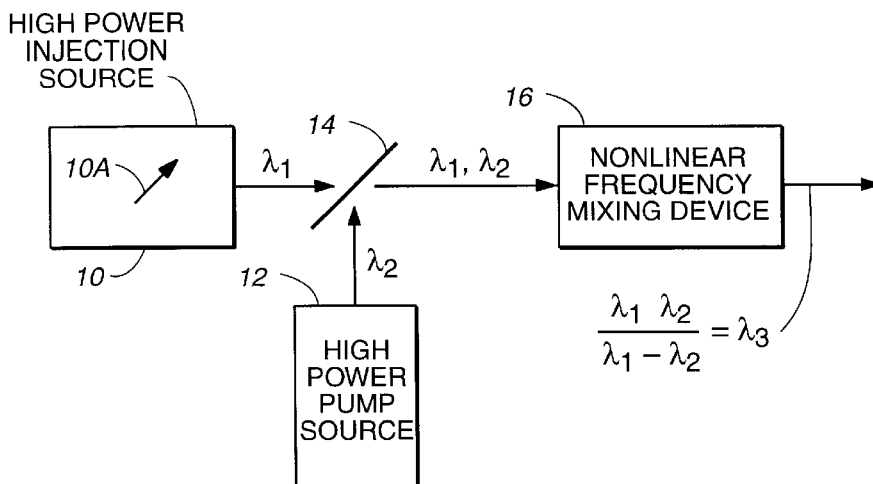
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Assistant Examiner—Robert E. Wise
Attorney, Agent, or Firm—W. Douglas Carothers, Jr.

[57] **ABSTRACT**

Laser diode pumped mid-IR wavelength systems include at least one high power, near-IR wavelength, injection and/or sources wherein one or both of such sources may be tunable providing a pump wave output beam to a quasi-phase matched (QPM) nonlinear frequency mixing (NFM) device. The NFM device may be a difference frequency mixing (DFM) device or an optical parametric oscillation (OPO) device. Wavelength tuning of at least one of the sources advantageously provides the ability for optimizing pump or injection wavelengths to match the QPM properties of the NFM device enabling a broad range of mid-IR wavelength selectivity. Also, pump powers are gain enhanced by the addition of a rare earth amplifier or oscillator, or a Raman/Brillouin amplifier or oscillator between the high power source and the NFM device. Further, polarization conversion using Raman or Brillouin wavelength shifting is provided to optimize frequency conversion efficiency in the NFM device.

30 Claims, 15 Drawing Sheets



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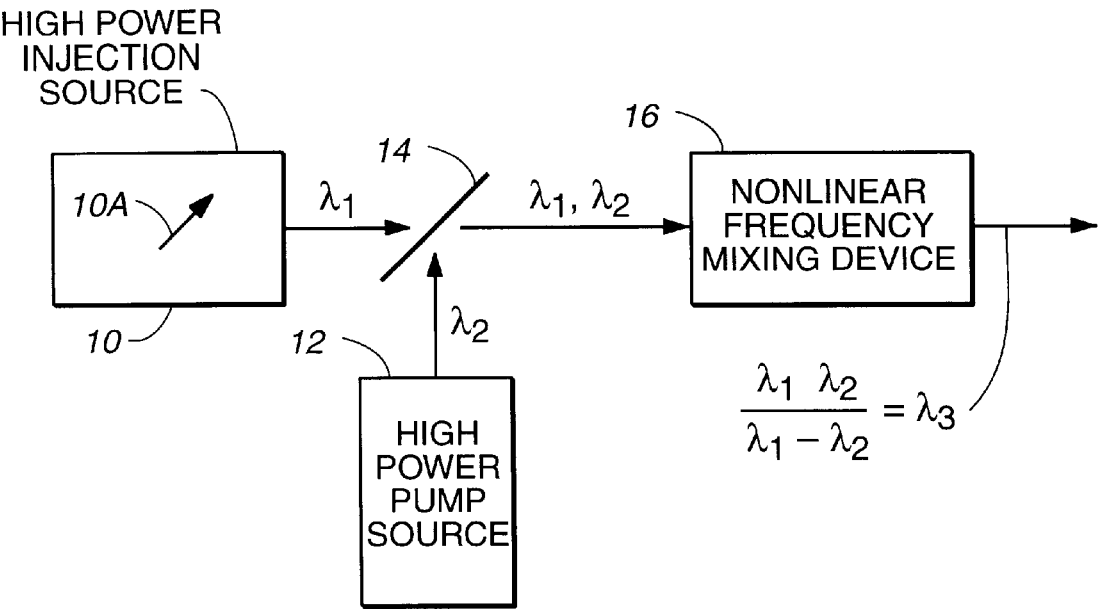


FIG._1A

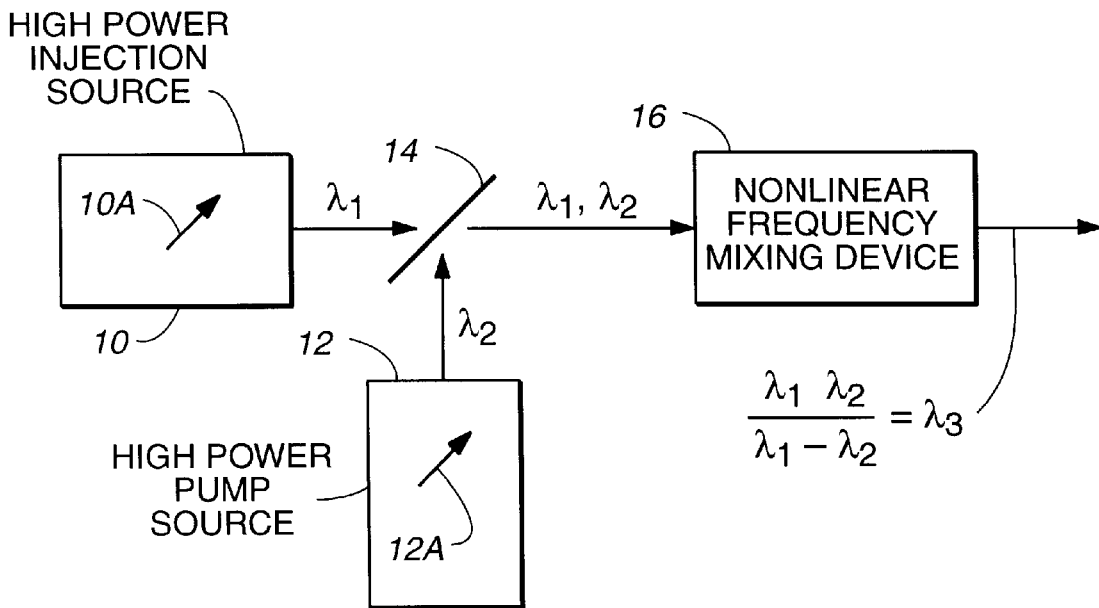


FIG._1B

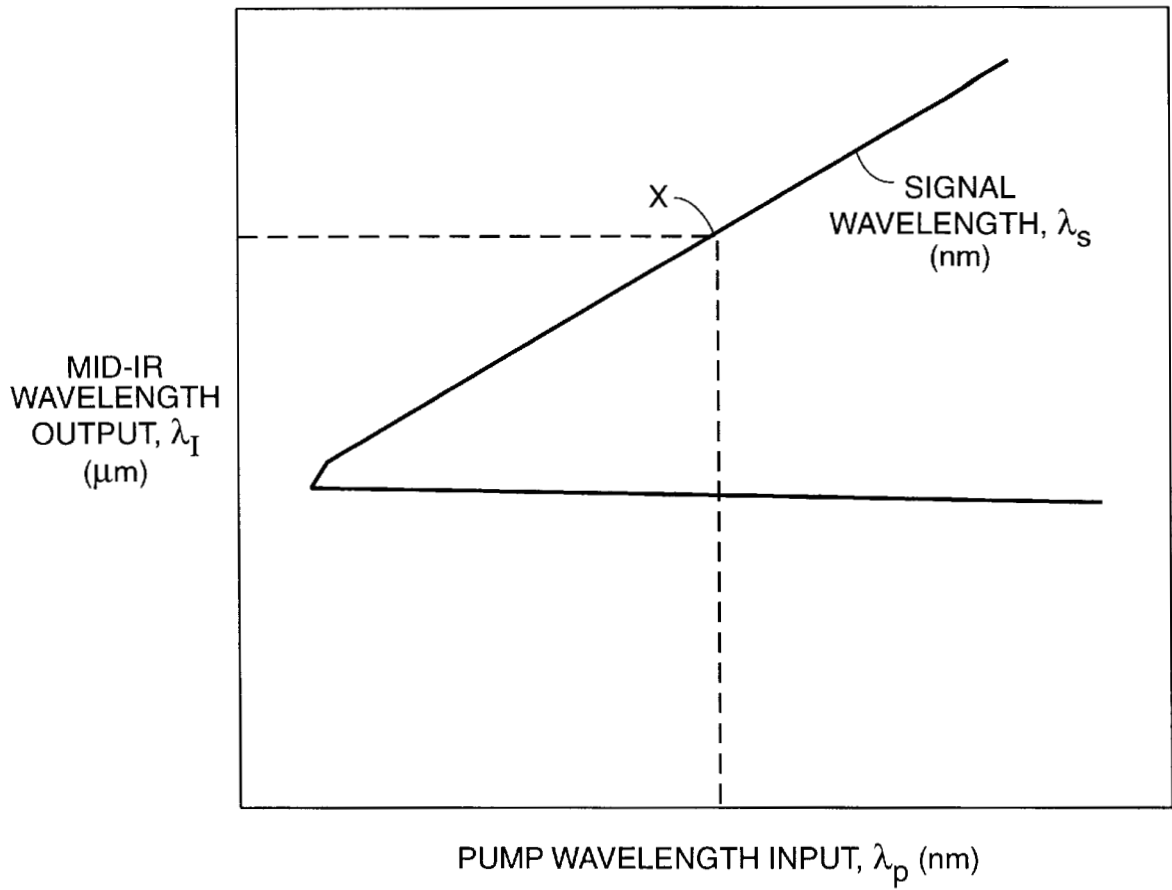


FIG._1C

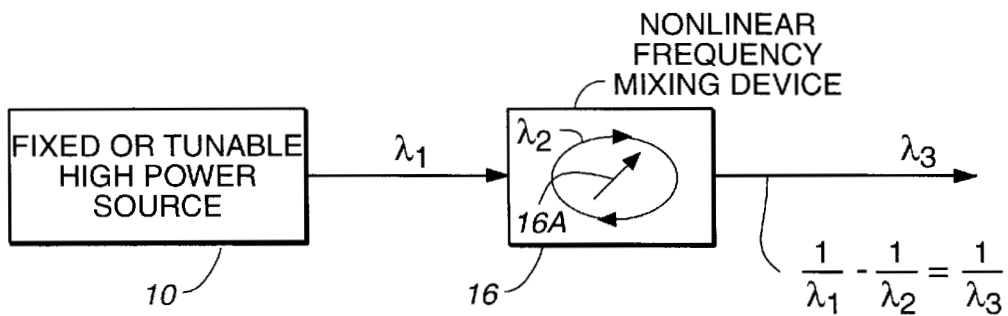


FIG._1D

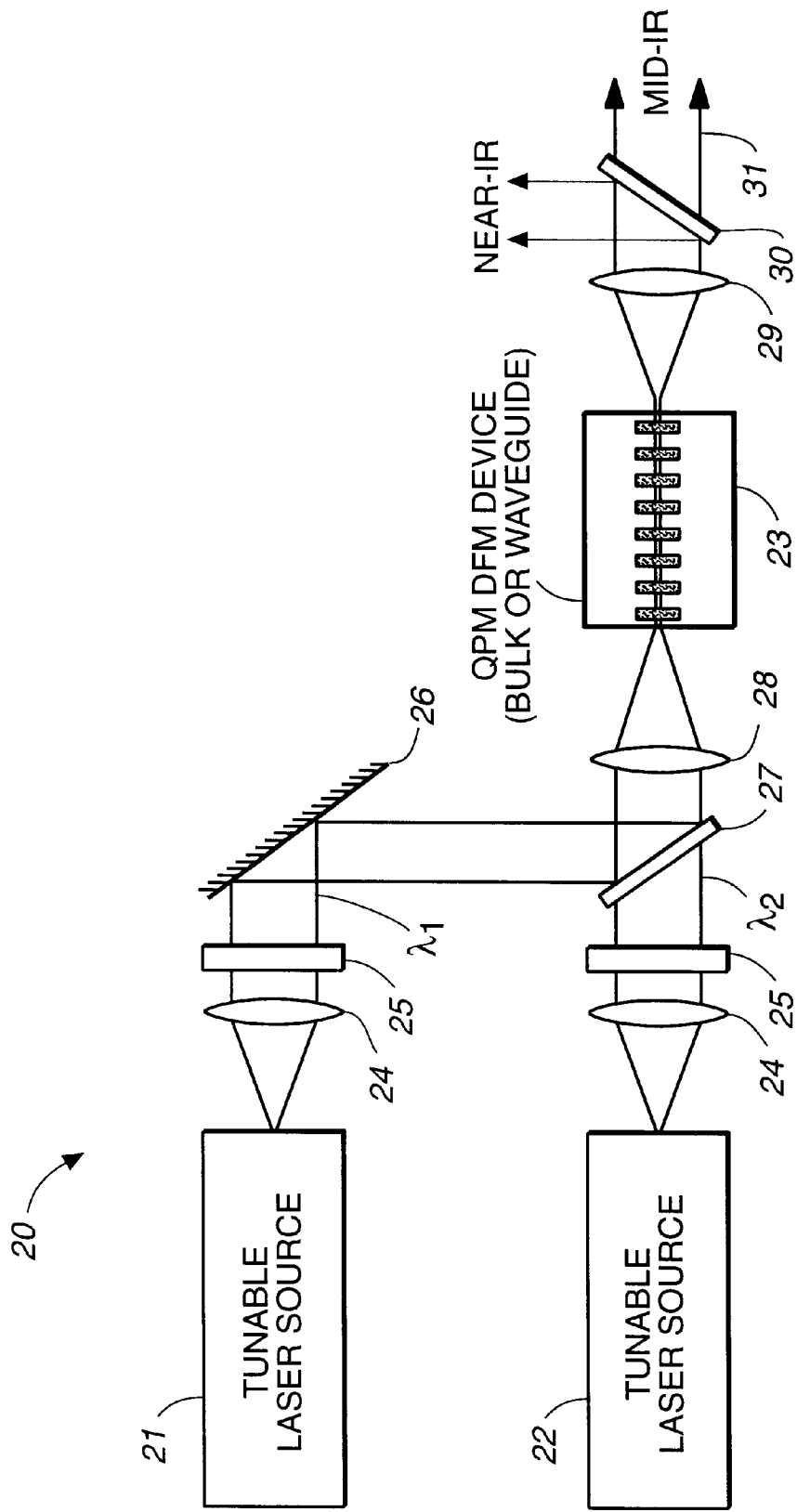


FIG.-2

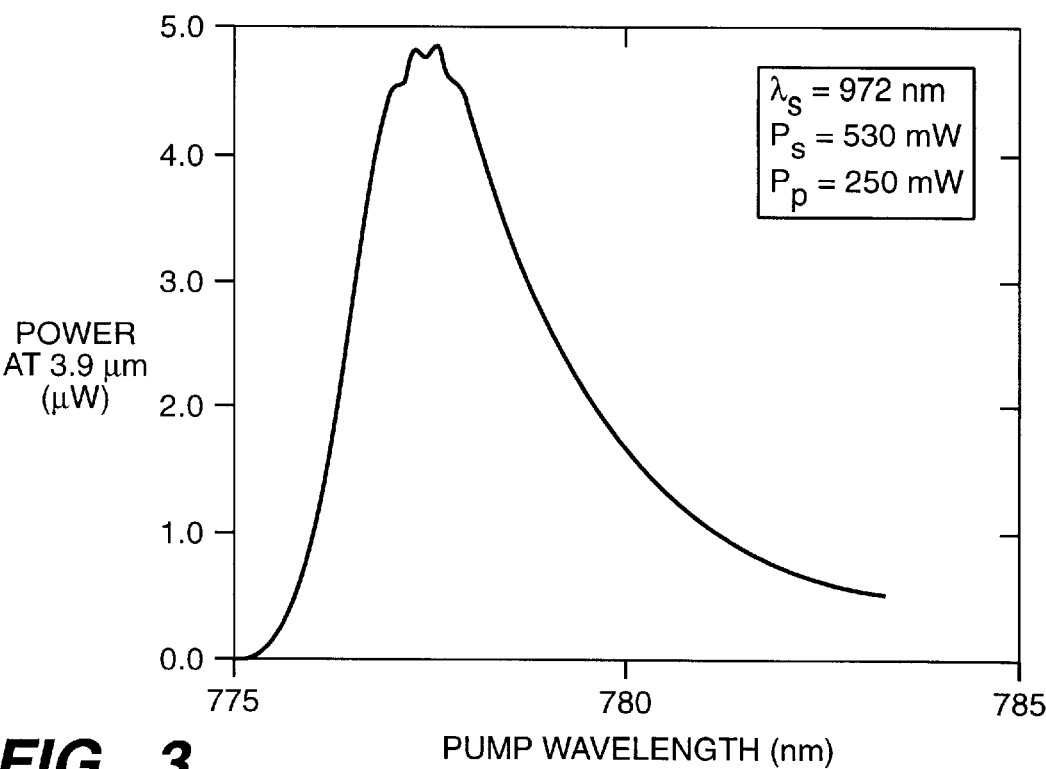


FIG._3

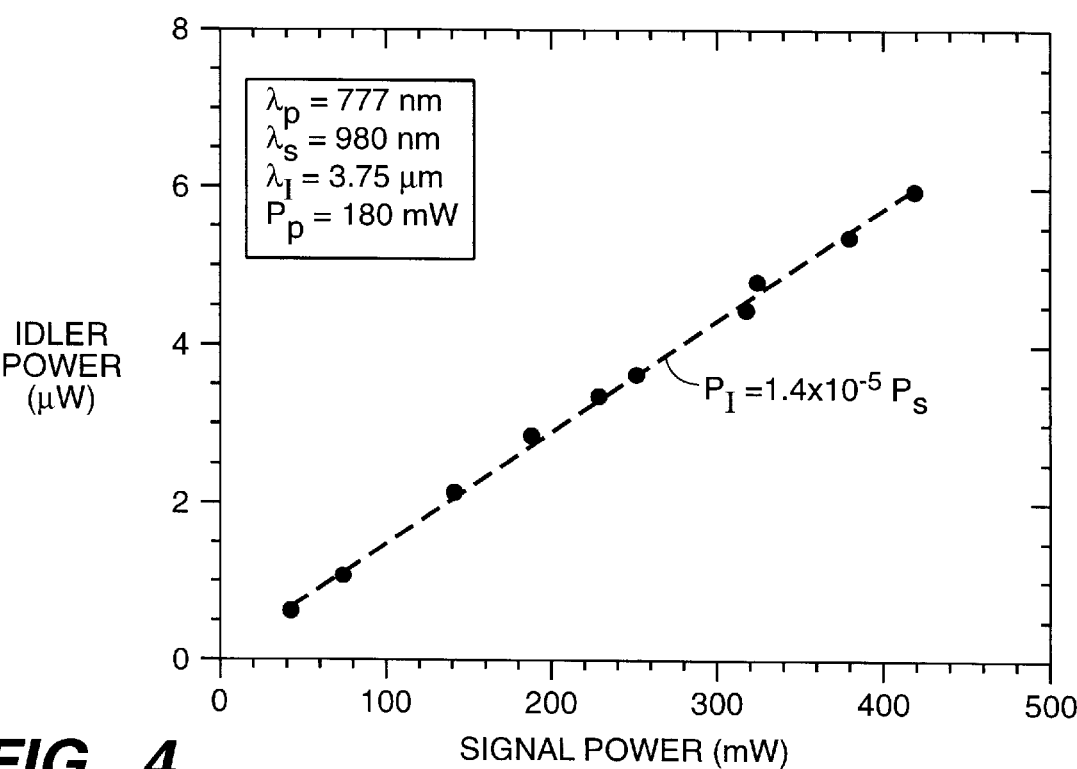


FIG._4

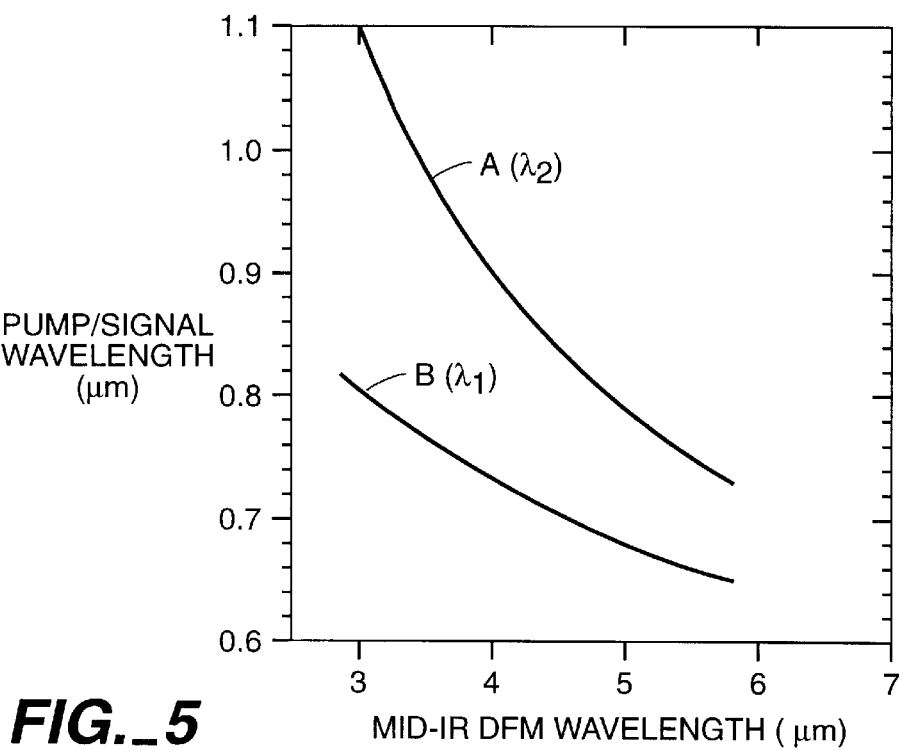


FIG._5

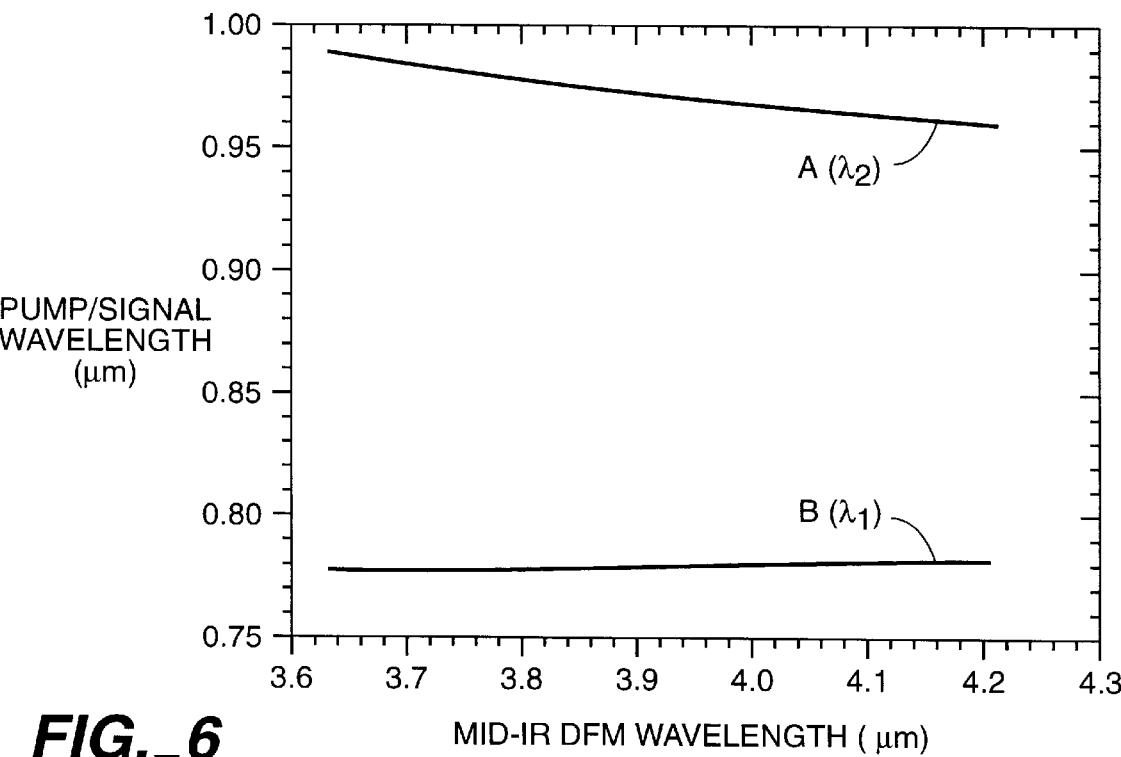


FIG._6

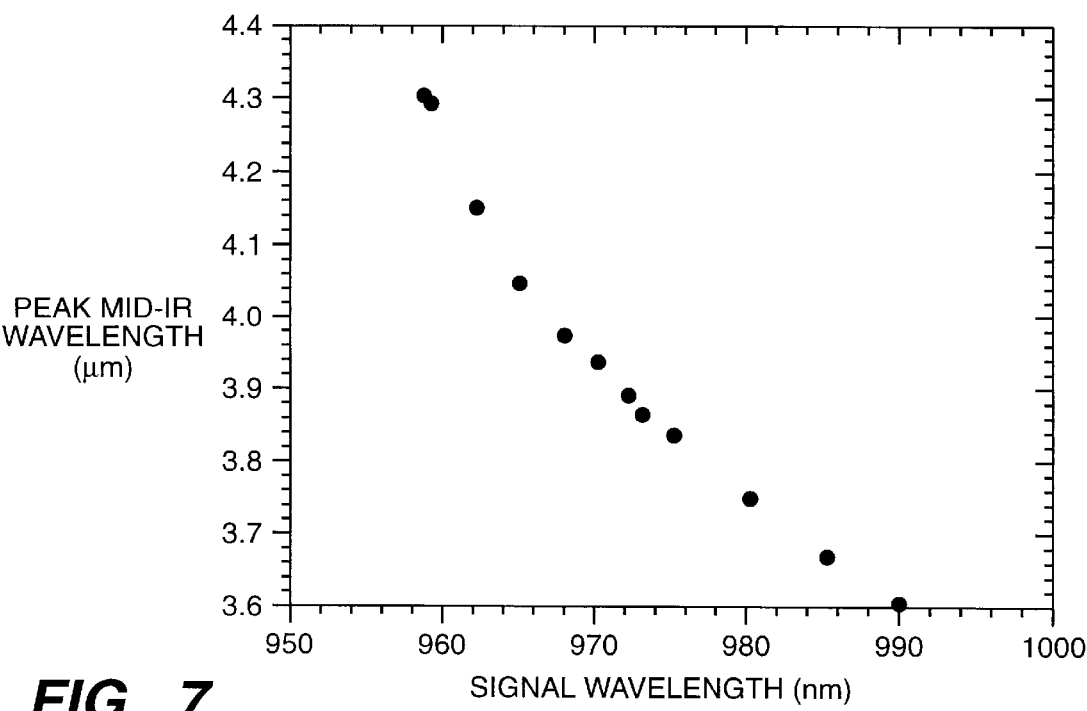


FIG._7

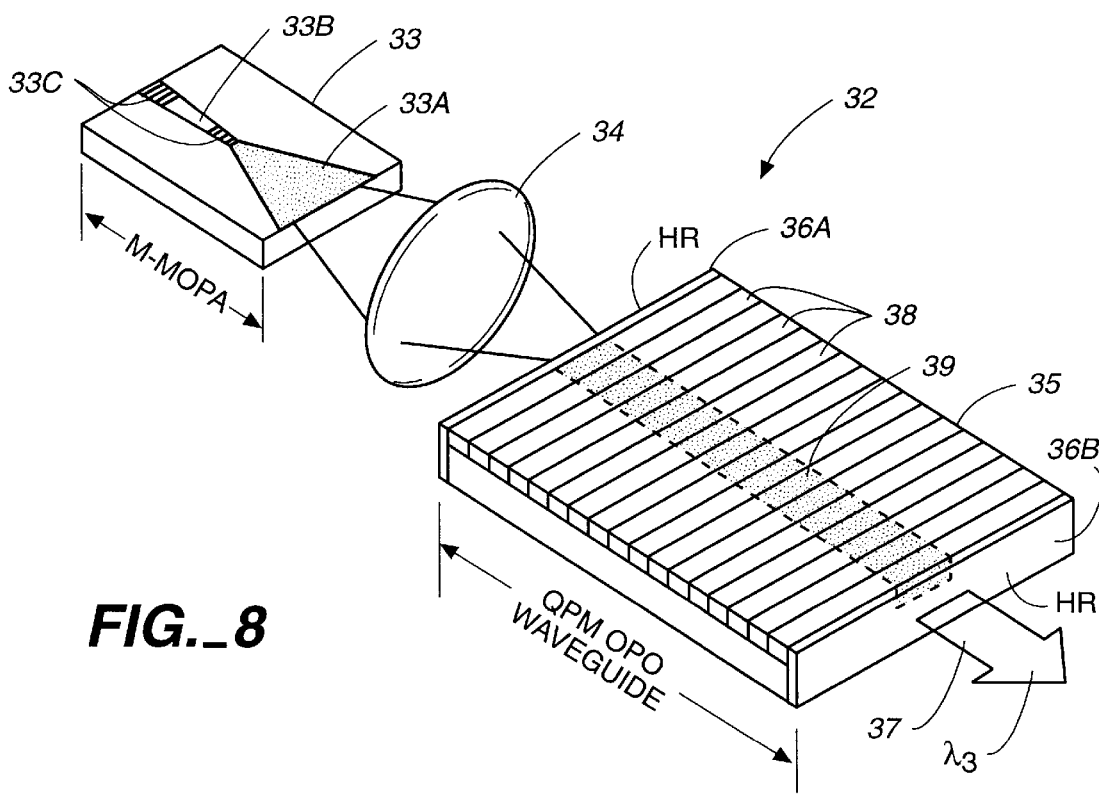


FIG._8

FIG. 9

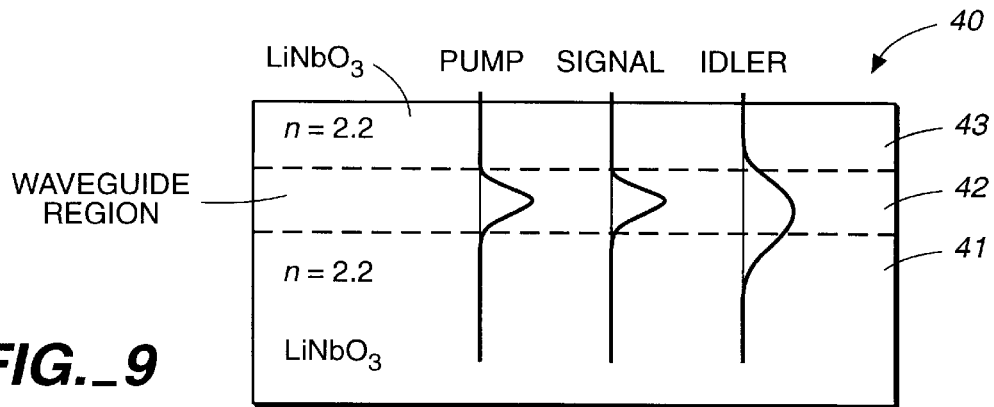


FIG. 10

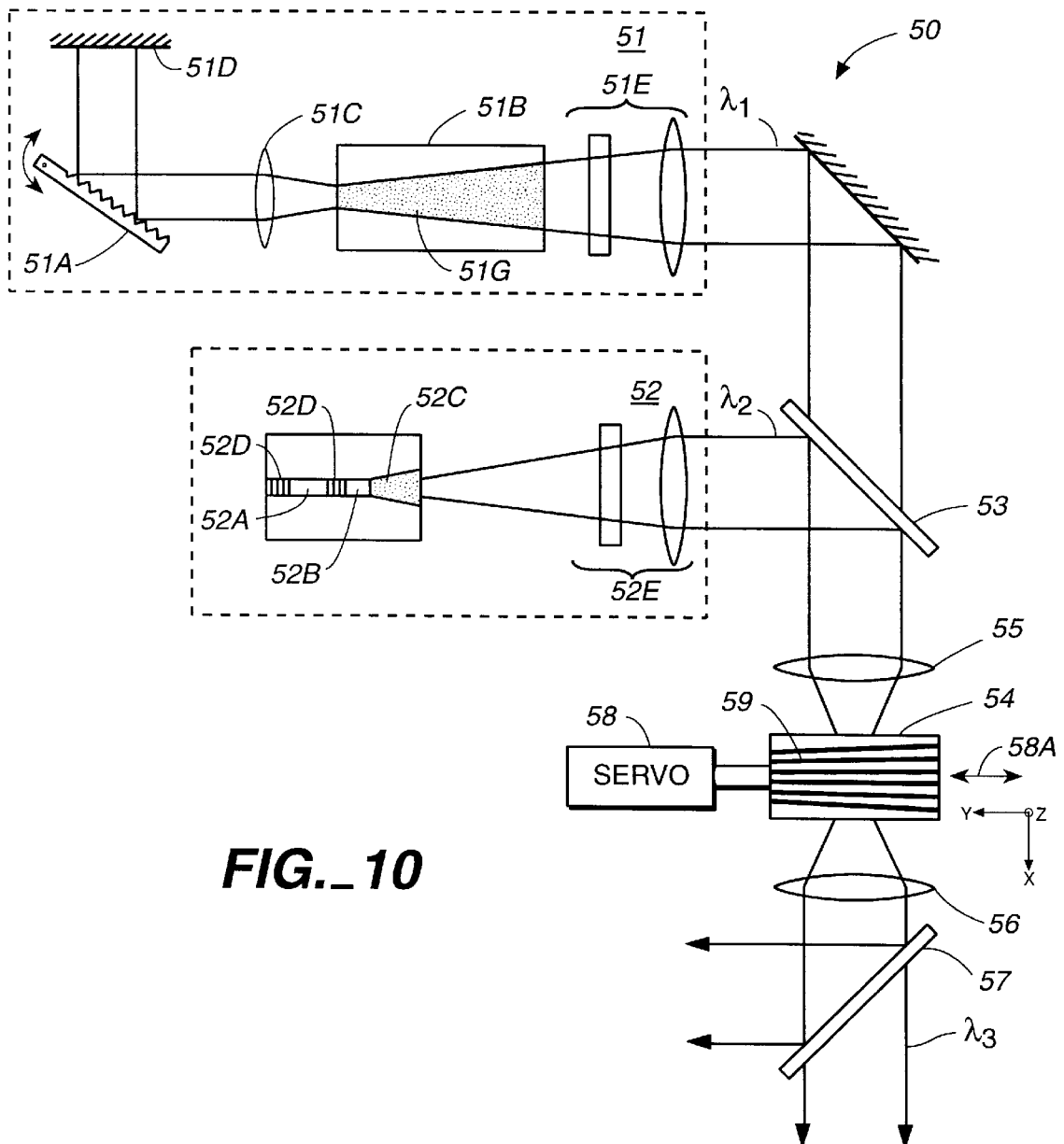


FIG._10A

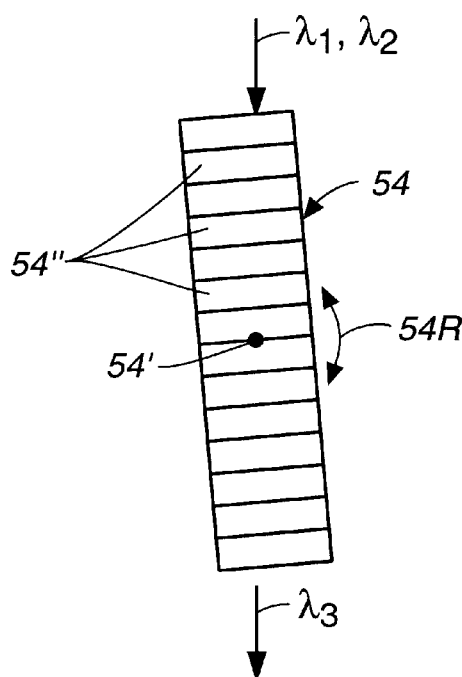
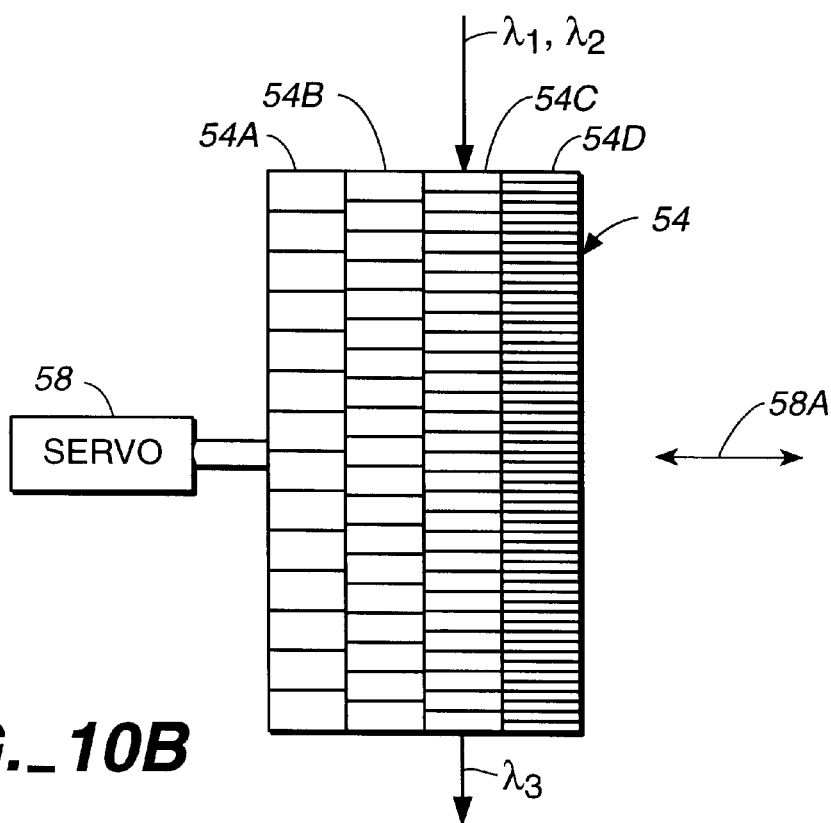
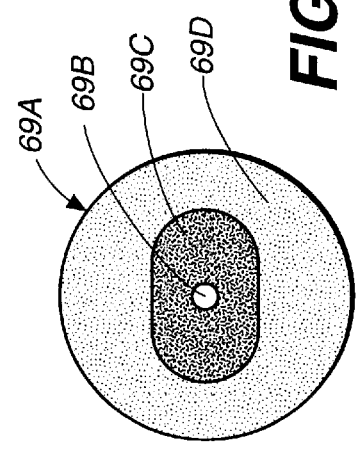
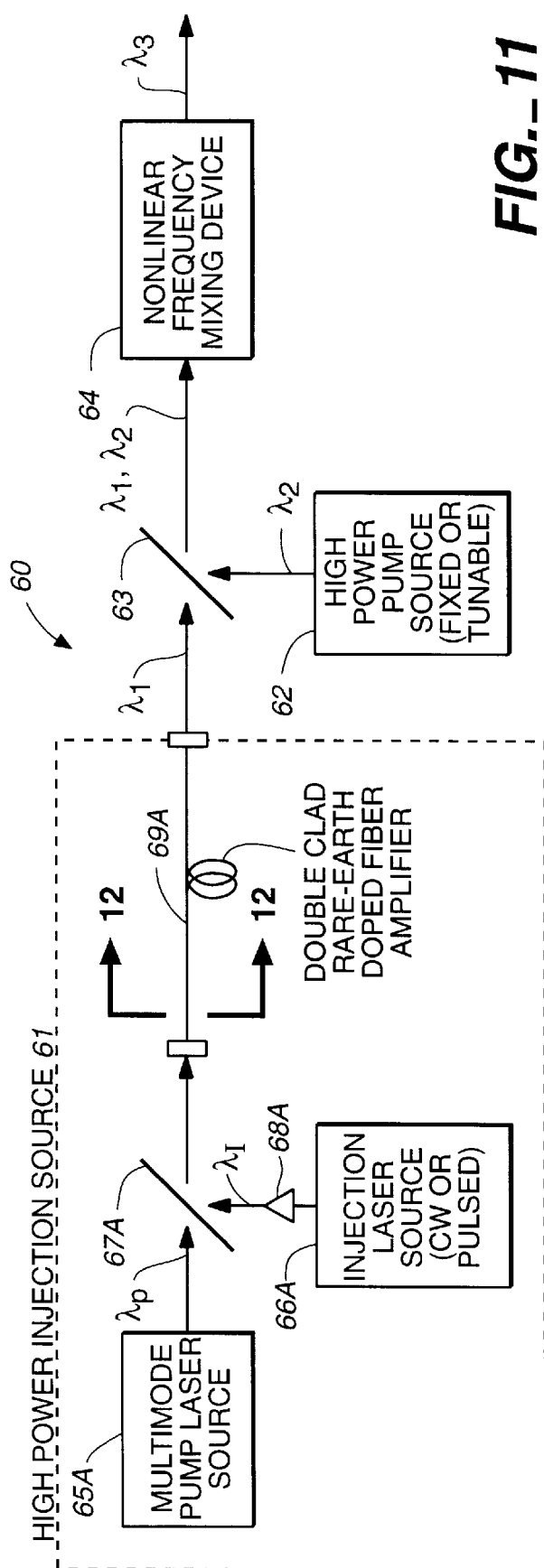
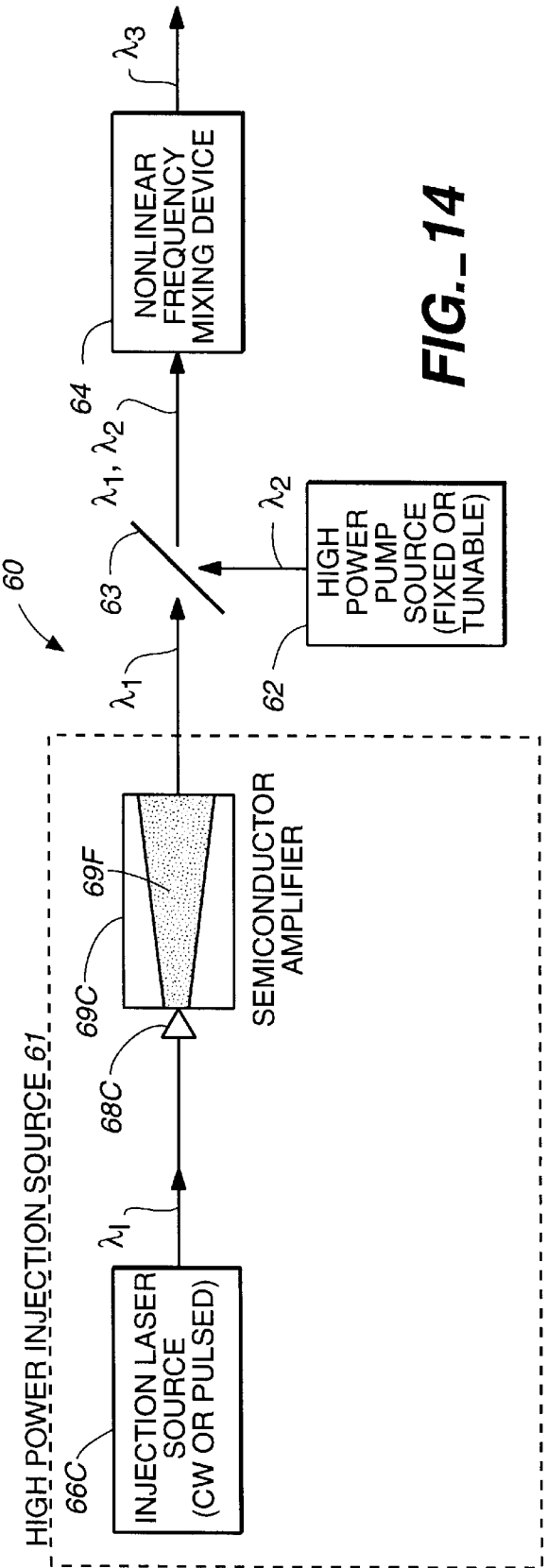
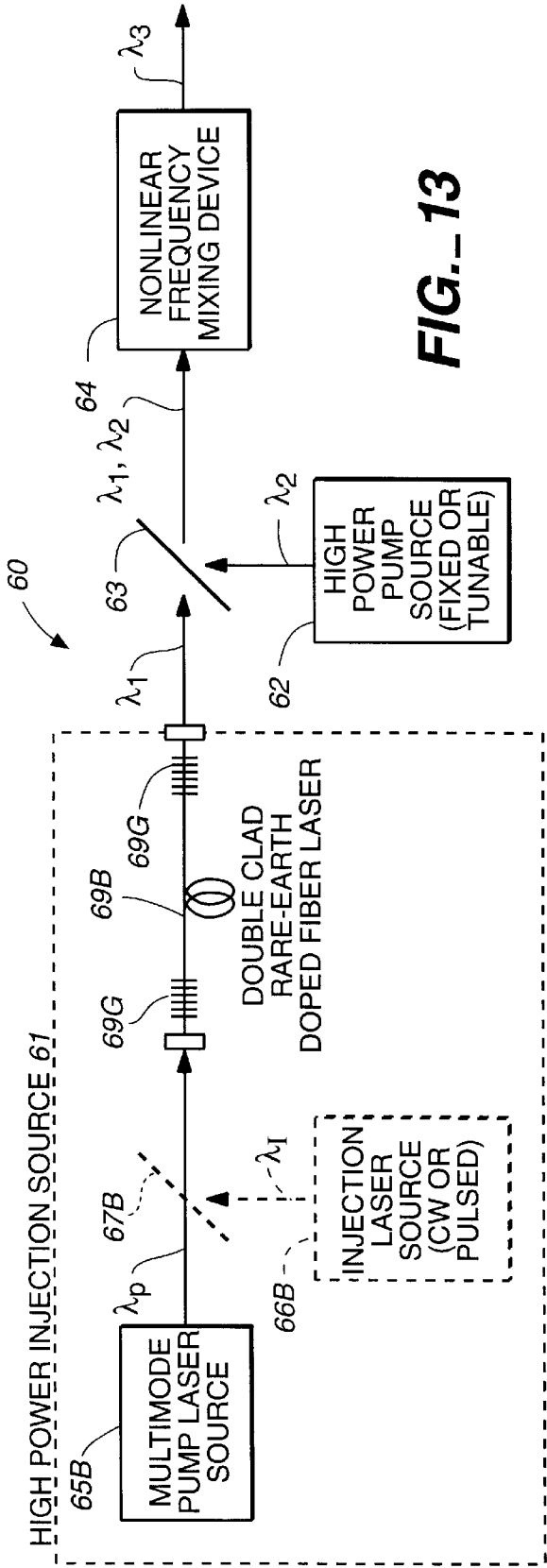


FIG._10B







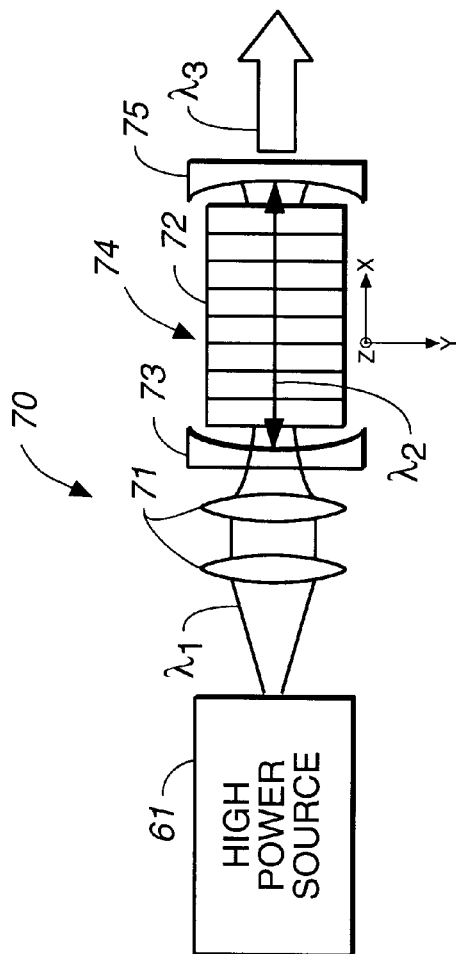


FIG. 15

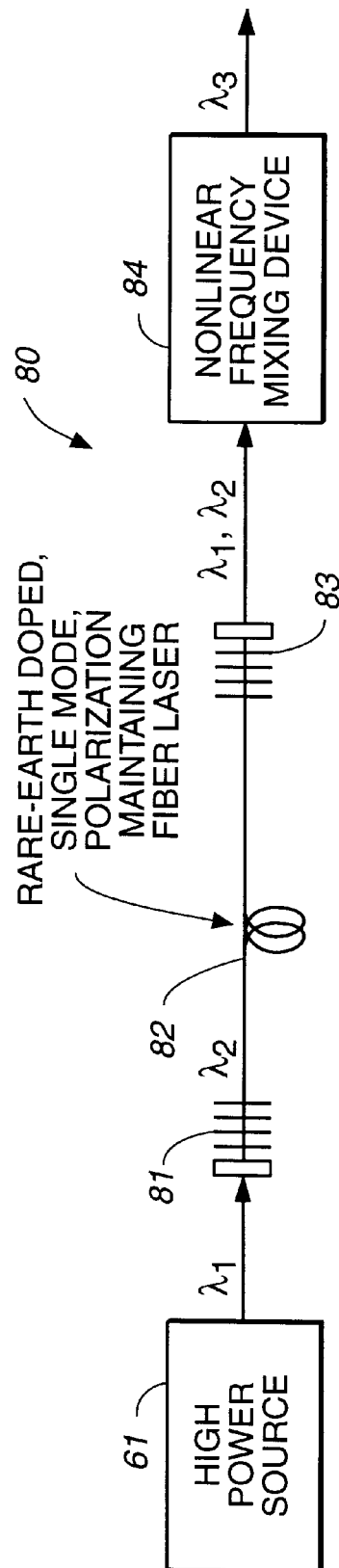


FIG. 16

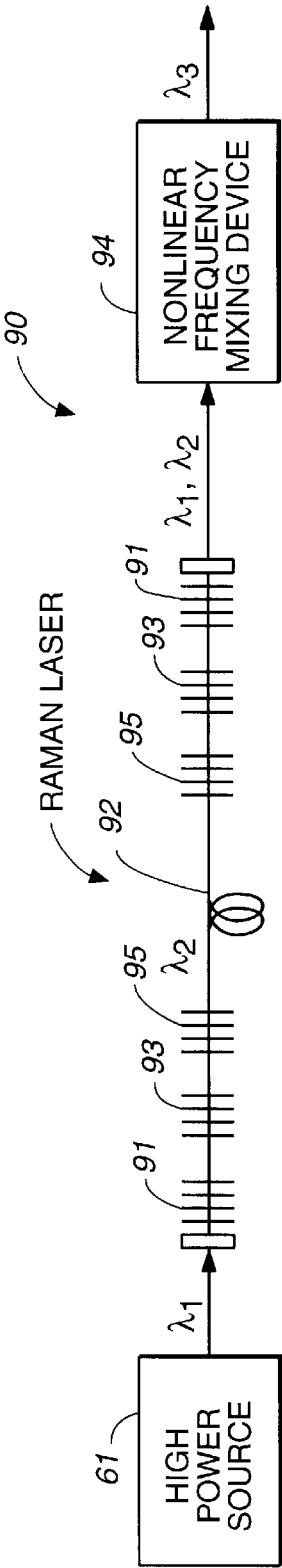


FIG. 17

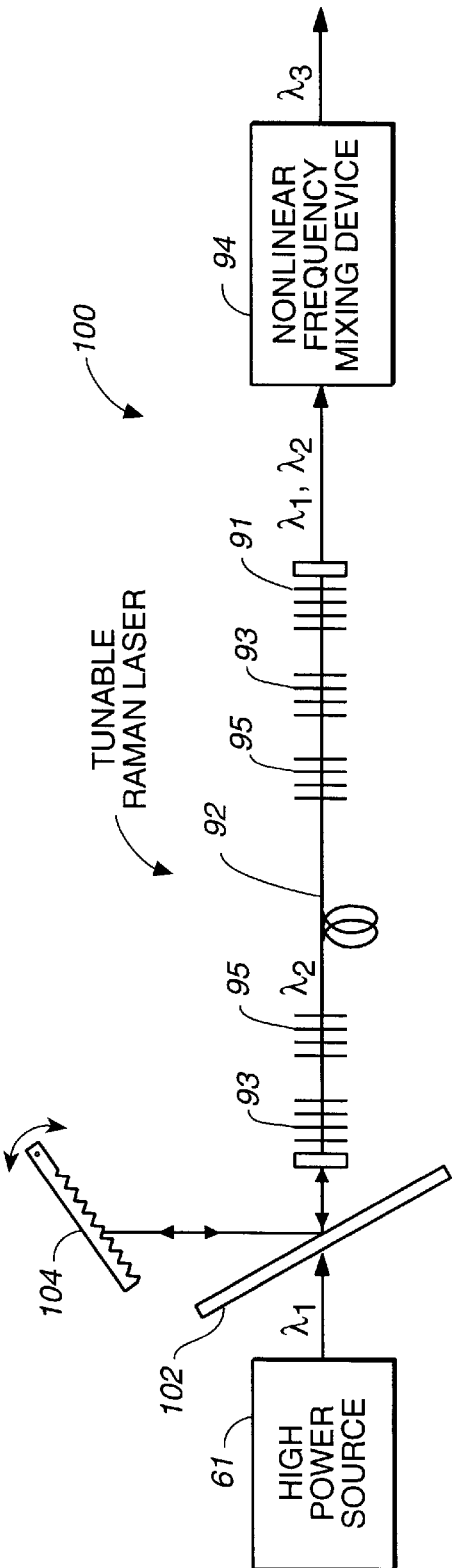


FIG. 18

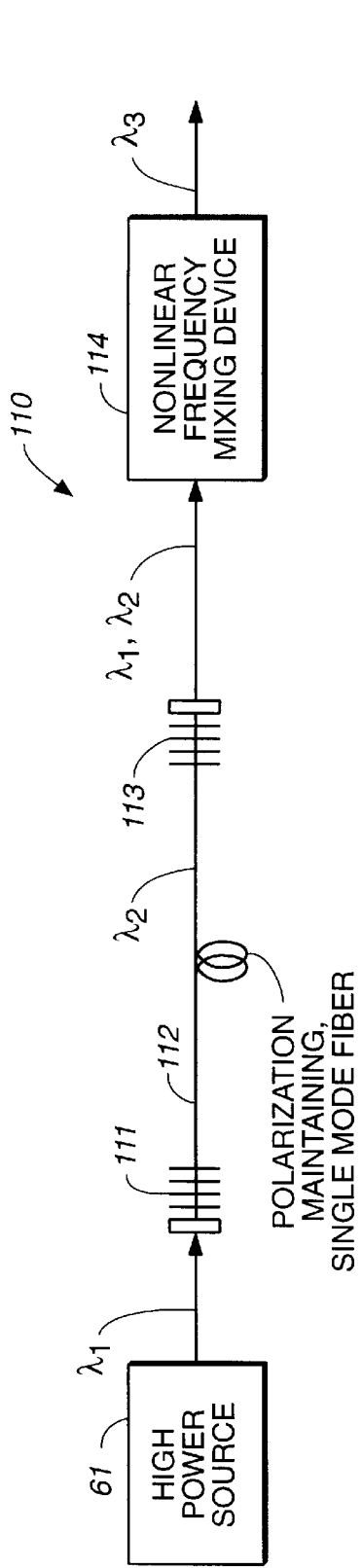


FIG. 19

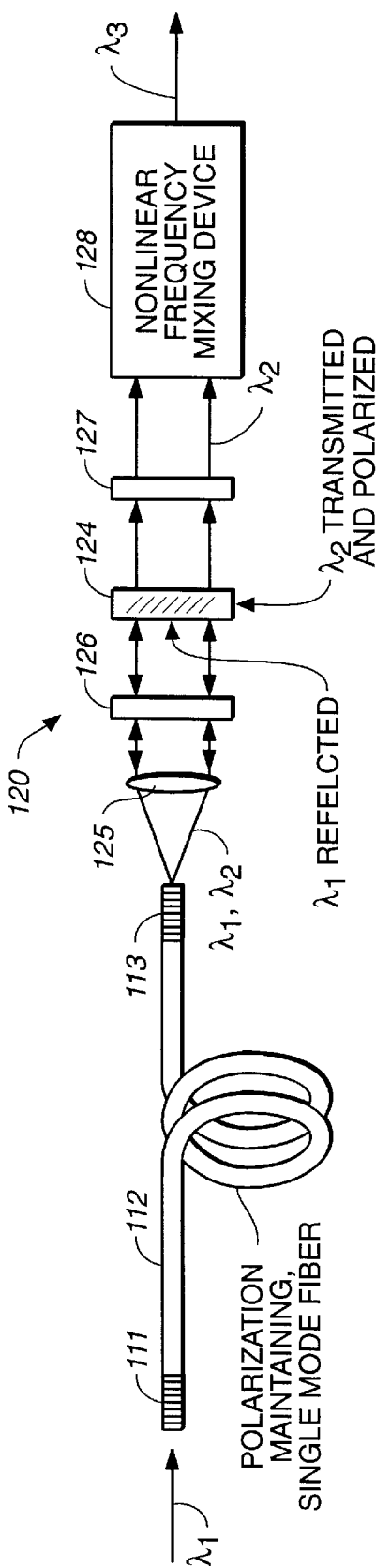


FIG. 20

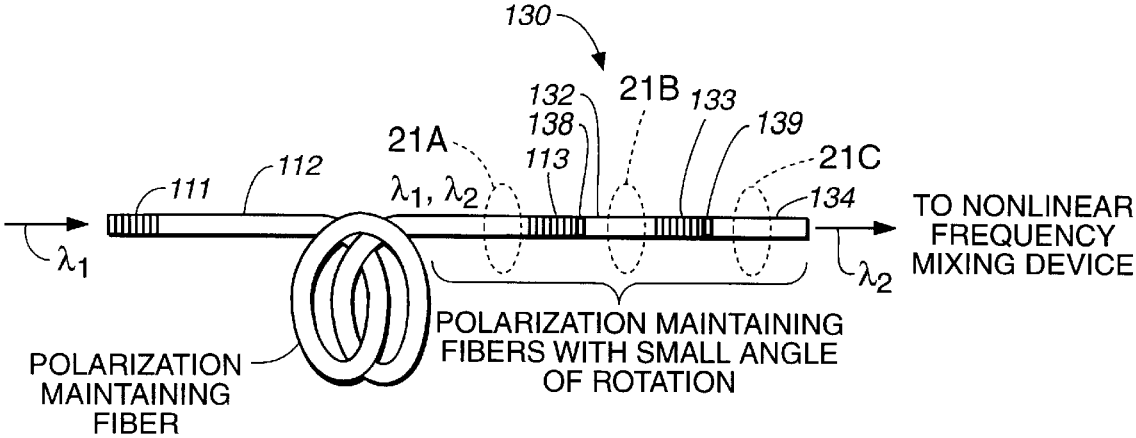


FIG. 21

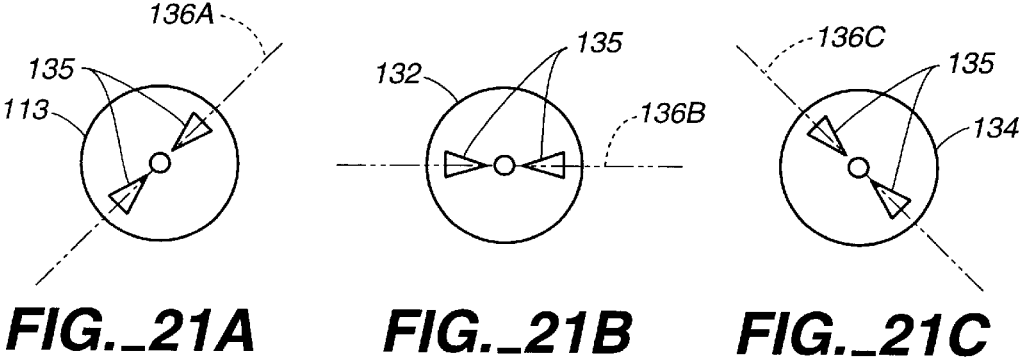


FIG. 21A

FIG. 21B

FIG. 21C

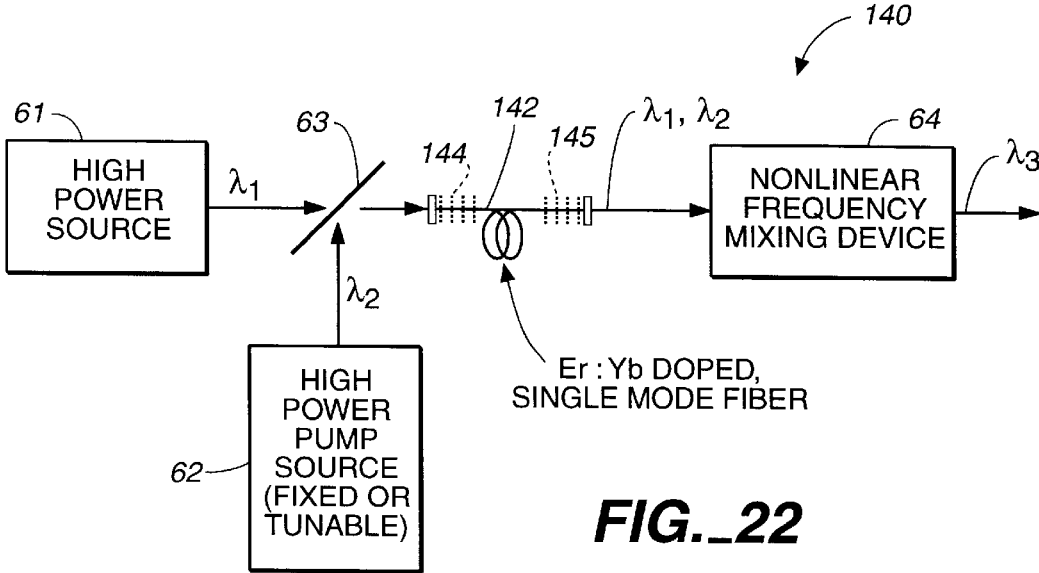
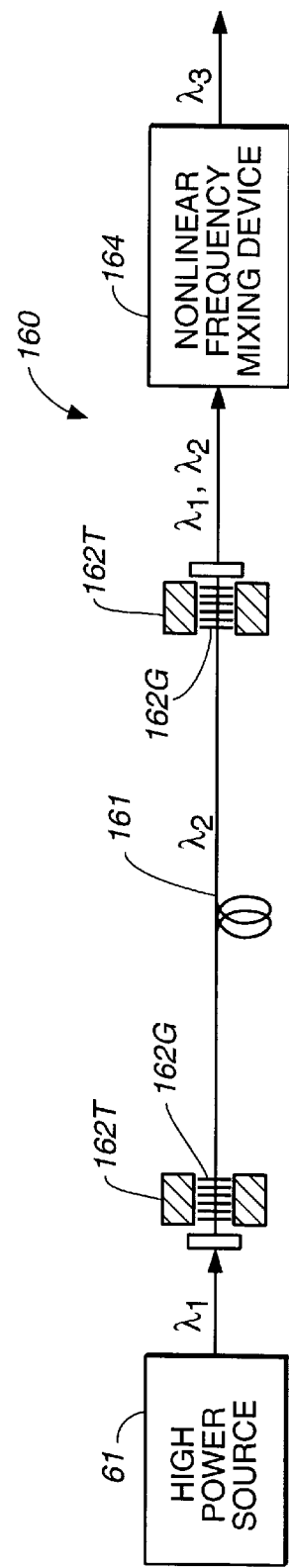
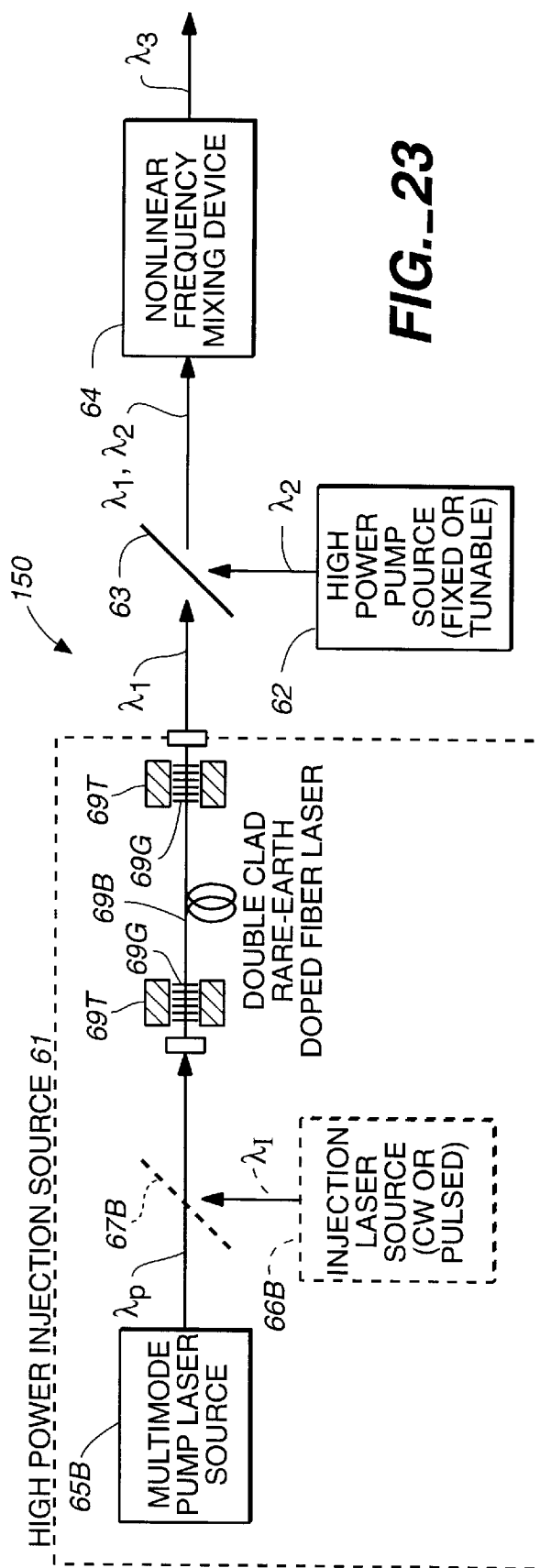


FIG. 22



HIGH POWER PUMPED MID-IR WAVELENGTH SYSTEMS USING NONLINEAR FREQUENCY MIXING (NFM) DEVICES

STATEMENT AS TO RIGHTS TO INVENTIONS
MADE UNDER FEDERALLY SPONSORED
RESEARCH AND DEVELOPMENT

This invention was made with government support under Contract No. NAS2-14200, awarded by the National Aviation Space Administration (NASA AMES) and under Contract No. DASG60-94-C-0043, awarded by the Defense Advanced Research Projects Agency (DARPA). The government has certain right in the invention.

FIELD OF THE INVENTION

This invention relates generally to frequency conversion systems and high power sources for such systems, and more particularly to wide-range frequency systems that convert coherent near-infrared radiation to coherent mid-infrared radiation using nonlinear frequency mixing or conversion, such as by difference frequency mixing (DFM) and optical parametric oscillation (OPO).

BACKGROUND OF THE INVENTION

There is a great interest and need for developing compact, reliable high power mid-infrared radiation (mid-IR) sources for many types of applications, such as, spectroscopy, environmental monitoring, gas and chemical sensing and manufacturing process control. The most serious limitations to practical mid-IR sources has been the complexity of the near-IR pump source required and the cost, stability and reliability of nonlinear mixing mediums. However, nonlinear frequency mixing of high power near-IR laser diode sources would be an attractive technique for generating broadly tunable coherent mid-IR frequencies, such as in the range of about 2.0 μm to 5.0 μm .

The use of high power laser diodes for frequency conversion have been contemplated for sum or difference frequency mixing (SFM or DFM) applications, such as shown in FIG. 6 of U.S. Pat. No. 5,321,718, which is commonly owned by the assignee of this application and is incorporated herein by reference thereto. Disclosed are a pair of high tunable power laser diodes tuned to emit radiation of different wavelengths λ_1 , λ_2 , the beams of which are subsequently combined and provided as input to a nonlinear crystal device for difference frequency mixing producing a mid-infrared output of wavelength $\lambda_3 = \lambda_1 \cdot \lambda_2 / (\lambda_1 - \lambda_2)$ or for sum frequency mixing producing blue or green light output of wavelength $\lambda_3 = \lambda_1 \cdot \lambda_2 / (\lambda_1 + \lambda_2)$.

Presently, there are no reliable room temperature operated, broadly tunable mid-IR sources that are sufficiently compact to provide for an output over broad mid-range infrared radiation. No direct room temperature laser diode sources are available at wavelengths longer than about 2.4 μm . Other sources, for example, employ comparatively large, higher than room temperature operated lasers, such as a Ar^+ laser pumping a Ti:sapphire, YAG laser or a dye laser. Moreover, nonlinear frequency mixing to achieve desired long wavelength frequencies requires better frequency conversion performance in presently available materials. The existing nonlinear frequency mixing (NFM) techniques employed for frequency doubling or extending are quasi-phase matching (QPM) with difference frequency mixing (DFM) and optical parametric oscillation (OPO).

So far, mid-IR generation by difference frequency mixing (DFM) has been demonstrated using laser diodes, in lieu of gas lasers, with a AgGaS_2 and AgGaSe_2 material utilizing noncritical birefringent phase matching (BPM) and, also, by quasi-phase matching (QPM) using LiNbO_3 waveguide material. An example of the former is found in U. Simon et al., "Difference Frequency Generation in AgGaS_2 by Use of Single Mode Diode Laser Pump Sources", *Optics Letters*, Vol. 18(13), pp. 1062-1064 (Jul. 1, 1993), which involved the feasibility of using two single mode laser diodes as pump sources mixed in AgGaS_2 crystal generating about 3 nW of low end, mid-IR power at about 2 μm . Tunability is suggested but is limited to tuning by means of varying the temperature and current of the diodes by permitting their emission wavelength to be tuned over its narrow bandwidth, e.g., 2 nm which would correspond to about a range of 18 nm tuning of the mid-IR wavelength from the AgGaS_2 crystal (page 1063, col. 1, first full paragraph). Moreover, it has been proposed by U. Simon et al. in the article, "Difference frequency Mixing in AgGaS_2 by Use of a High Power GaAlAs Tapered Semiconductor Amplifier at 860 nm", *Optics Letters*, Vol. 18(22), pp. 1931-1933 (Nov. 15, 1993) to provide one of the sources, the signal or injection source, as a single mode, master laser diode pumping a semiconductor flared amplifier to enhance the pumping power output to about 1.5 W as input, together with the output from a Ti:sapphire laser as the pumping wave to the QPM DFM AgGaS_2 crystal.

As for the employment of LiNbO_3 waveguides, the article of L. Goldberg et al., "Difference Frequency Generation of Tunable Mid-IR in Bulk Periodically Poled LiNbO_3 ", *Advance Solid-State Lasers*, (Post-deadline paper), pp. PD23-1 to PD23-3 (Jan. 30, 1995) and L. Goldberg et al., "Widely Tunable Difference Frequency Generation in QPM- LiNbO_3 ", Paper CPD49, Conference on Laser and Electro-Optics (CLEO May, 1995), discloses a tunable QPM DFM in a bulk periodically poled LiNbO_3 using Nd:YAG and Ti:sapphire laser as pumping sources with the DFM wavelength tuned over a range of about 3.0 μm to 4.0 μm by tuning the Ti: sapphire laser or rotating the QPM LiNbO_3 crystal to change the effective grating period. The disadvantage of the foregoing systems for achieving mid-IR generation is the lack of room temperature, mid-IR tunability over a large expansive mid-IR range of 2.0 μm to 5.0 μm and lack of a delivery system for mid-IR generation that is compact in size, less costly and not requiring large size solid state and gas lasers operating at elevated temperatures requiring large operating powers.

LiNbO_3 waveguide material is a robust, relatively inexpensive, highly reliable nonlinear material for DFM, and QPM permits the material to be tailored to mix arbitrary laser diode wavelengths through the choice of an appropriate ferroelectric domain reversal period or periodic poling. Recent advances in electric field poling of LiNbO_3 waveguide material allows QPM to be implemented in bulk interactions and has been employed in demonstrating mid-IR optical parametric oscillation (OPO). See L. E. Myers et al., "Quasi-Phase Matched 1.064 μm -Pumped Optical Parametric Oscillator in Bulk Periodically Poled LiNbO_3 ", *Optics Letters*, Vol. 30(1), pp. 52-54 (Jan. 1, 1995) and W. K. Burns et al., "Second Harmonic Generation in Field Poled, Quasi-Phase Matched, Bulk LiNbO_3 ", *IEEE Photonics Technology Letters*, Vol. 6(2), pp. 252-254 (February, 1994). However, mid-IR generation has been demonstrated in quasi-phase matching (QPM) crystals relative to such laser diode sources only for relatively shorter wavelength applications and not reliably extended to more desired

mid-IR wavelength applications. Moreover, as applied to AgGaS₂ and AgGaSe₂ crystals, the full spectral range of mid-IR generation cannot be easily derived because the input wavelength range required to cover the full 2.0 μm to 5.0 μm mid-IR range is very broad for noncritical phase matching.

What is needed is a mid-IR generating system providing for noncritical phase matching over a wide range of near-IR input wavelengths at room temperature that can be frequency mixed to selectively provide a desired mid-IR wavelength over the entire mid-IR range from about 2.5 μm to 5 μm .

An object of this invention is the provision for mid-IR frequency conversion over a wide frequency range.

Another object of this invention is the provision for high power, semiconductor/optical amplifier/laser sources as applied to nonlinear frequency mixing devices, e.g., high power laser diodes, master oscillator power amplifier (MOPA) devices high power fiber amplifier or laser, laser or amplifier devices, Raman or Brillouin amplifiers or lasers, and rare earth single mode fiber amplifiers and lasers.

Another object of this invention is the provision of the use of near-IR laser diode sources to generate broadly tunable coherent mid-IR radiation, such as tunable across the mid-IR range of 2 μm to 5 μm .

Another object of this invention is the provision of a compact, room temperature, broadly tunable coherent source for selectively tuning a desired mid-IR wavelength.

Another object of this invention is the provision of high efficiency buried non-linear waveguide structures using quasi-phase matching (QPM) to convert developed near-IR power from room temperature laser sources to mid-IR power for use, for example, in a large spectrum of analysis, sensing and monitoring applications.

SUMMARY OF THE INVENTION

According to the system of this invention, a broadly tunable laser diode pumped mid-IR wavelength source comprises a pump source comprising combinations of one or more different types of high power semiconductor or optical amplifier or lasers sources, such as a master oscillator power amplifier (MOPA), fiber amplifiers or lasers, tunable laser diodes, and Raman or Brillouin amplifiers or lasers, for injection and pump wavelength input to a nonlinear frequency mixing (NFM) device, such as a quasi-phase matching difference frequency mixing (QPM DFM) device or a quasi-phase matching optical parametric oscillation (QPM OPO) device to selectively provide a mid-IR frequency as output in the range of 2.0 μm to 5.0 μm . By extending the tunability of the pump source wavelengths for QPM frequency mixing, the range of possible mid-IR wavelengths is greatly extended without being significantly affected by the absorption limitations of the crystal material employed for frequency mixing. Suitable materials in the past, e.g., AgGaS₂ and AgGaSe₂, provided tunability for noncritical birefringent phase matching required for large input wavelength tuning ranges such as between 680 nm to 1100 nm to possibly achieve the full mid-IR radiation spectrum. However, by employing QPM nonlinear crystals, such as LiNbO₃, input mixing wavelengths can be tuned over shorter wavelength ranges to provide for broader tuning selectability of mid-IR wavelengths. As an example, QPM DFM can be accomplished over the full mid-IR radiation spectrum with one fixed signal wavelength input of 1100 nm and the other pump wavelength tuned between the narrow range of 775 nm to 900 nm or by mixing the output

wavelengths of two separate tunable laser diodes one tunable in the near-IR range of 730 nm to 833 nm and the other tunable in the near-IR range of 1000 nm to 1150 nm.

Another aspect of this invention is the provision of polarization maintaining fibers to provide linearly polarized light output to a nonlinear frequency mixing (NFM) device or other polarization input required device. In cases where the polarization of light input into the NFM device is polarized such that it will not experience efficient frequency conversion, an optical polarizing converter system is provided at the output of the fiber to compensate for this condition. Polarization maintaining fiber may function as well as an amplifier, particularly in the case of input to QPM DFM devices and as a laser, particularly in the case of input to QPM OPO devices. In these applications, the fiber may be rare earth doped or co-doped, or operate with Raman gain shift or Brillouin gain shift.

Other objects and attainments together with a fuller understanding of the invention will become apparent and appreciated by referring to the following description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic illustration of a first configuration of a tunable high power, laser diode mid-IR wavelength source employing a NFM device and two high power injection/pump input sources wherein one of them is tunable to achieve a selectively tuned mid-IR wavelength idler output.

FIG. 1B is a schematic illustration of a second configuration of a tunable high power, laser diode mid-IR wavelength source employing a NFM device and two high power injection/pump input sources wherein both of them are tunable to achieve a selectively tuned mid-IR wavelength idler output.

FIG. 1C is a graphic illustration of the general relationship between pump, injection (signal) and idler wavelength selection employing a tunable high power, laser diode mid-IR wavelength source.

FIG. 1D is a schematic illustration of a third configuration of a fixed or tunable high power, laser diode mid-IR wavelength source employing a NFM device and one input laser diode pump source wherein either the laser diode and/or the non-linear frequency mixing device is tunable to achieve a selectively tuned mid-IR wavelength output.

FIG. 2 is a more detailed embodiment based upon the embodiment of FIG. 1B employing a QPM waveguide for single pass, difference frequency mixing (DFM).

FIG. 3 is a graphic illustration of mid-IR power output in μW for a given mid-IR wavelength versus near-IR pumping wavelength input in nanometers for a tunable high power, laser diode pumped mid-IR wavelength source according to FIG. 1B.

FIG. 4 is a graphic illustration of DFM idler or mid-IR power versus signal power for fixed pump power for the tunable high power, laser diode pumped mid-IR wavelength source according to FIG. 1B.

FIG. 5 is a graphic illustration of input pump/signal wavelength combinations for wavelength phase matching in AgGaS₂ crystal.

FIG. 6 is a graphic illustration of input pump/signal wavelength combinations for wavelength quasi-phase matching in a periodic poled LiNbO₃ crystal.

FIG. 7 is a graphic illustration of peak output mid-IR wavelengths to input signal wavelengths for the tunable high

power, laser diode pumped mid-IR wavelength source according to FIG. 1B using a periodic poled LiNbO₃ crystal as the NFM device.

FIG. 8 is a perspective view of a more detailed embodiment based upon the configuration shown in FIG. 1D employing a QPM waveguide as a multiple pass, optical parametric oscillator (OPO).

FIG. 9 is a schematic side elevation of a buried QPM type waveguide for a NFM crystal device for use with the embodiments of this invention.

FIG. 10 is a more detailed schematic illustration of a embodiment based upon the configuration shown in FIG. 1A employing a NFM device having a progressive poling scheme comprising a monotonically changing poling period in the form of a laterally shiftable, fan-shaped poling period for varying the poling period relative to the propagating light input.

FIG. 10A is another embodiment of a progressive poling scheme comprising a rotatable NFM device for varying the poling period relative to the propagating light input.

FIG. 10B is still another embodiment of a progressive poling scheme comprising a laterally stepped poling pattern which is laterally shifted for varying the poling period relative to the propagating light input.

FIG. 11 is a schematic illustration of a high power, mid-IR wavelength pump source for a NFM device employing a fiber amplifier as an injection source.

FIG. 12 is an enlarged cross sectional view of the double-clad fiber amplifier of FIG. 11 taken along the line 12—12 of FIG. 11.

FIG. 13 is schematic illustration of a high power, mid-IR wavelength pump source for a NFM device employing a fiber laser source.

FIG. 14 is a schematic illustration of a high power, mid-IR wavelength pump source for a NFM device employing a semiconductor amplifier as an injection source.

FIG. 15 is a schematic illustration of a high power, mid-IR wavelength pump source for a QPM waveguide comprising a multiple pass, optical parametric oscillator (OPO).

FIG. 16 is a schematic illustration of a high power, mid-IR wavelength pump source employing a high power laser diode and fiber laser source with a rare earth doped, single mode, polarization maintaining fiber laser.

FIG. 17 is a schematic illustration of a high power, mid-IR wavelength pump source employing a Raman wave shift, single mode fiber laser to provide the second wavelength for frequency mixing.

FIG. 18 is a schematic illustration of a high power, mid-IR wavelength pump source employing a tunable fiber oscillator to provide the second wavelength for frequency mixing.

FIG. 19 is a schematic illustration of a high power, mid-IR wavelength pump source employing a polarization maintaining single mode fiber which may be amplifier or oscillator to provide the second wavelength for frequency mixing.

FIG. 20 is a detailed schematic illustration of portion of the embodiment shown in FIG. 19 utilized with a first polarization converter for polarization maintenance of the output beam to a NFM device or other such device.

FIG. 21 is a detailed schematic illustration of portion of the embodiment shown in FIG. 19 showing a second polarization converter for polarization maintenance of the output beam to a NFM device or other such device.

FIG. 22 is a second basic configuration of a tunable high power, laser diode mid-IR wavelength source according to FIG. 1B as combined with a fiber amplifier.

FIG. 23 is a schematic illustration of a high power, mid-IR wavelength pump source employing a tunable Raman wave shift, single mode fiber oscillator to provide the second wavelength for frequency mixing.

FIG. 24 is a detailed schematic illustration of portion of the embodiment shown in FIG. 13 employing a tunable rare-earth doped fiber amplifier as part of the high power pump source.

PREFERRED EMBODIMENT OF THE INVENTION

The following described mid-IR wavelength sources are primarily based on tunable frequency mixing of high power, near-IR laser diodes, MOPAs, fiber amplifiers or fiber lasers or oscillators, including fiber amplifiers or oscillators having polarization maintaining fibers, or rare earth doped fibers, or single mode of multimode fibers, or Raman/Brillouin wave-shift formed fibers. These mid-IR wavelength sources are attractive because, compared to what is readily available in the mid-IR wavelength range involving large, high temperature operating gas laser devices, these new devices offer broadly tunable coherent mid-IR output from a relatively low cost, compact, room temperature operating device easily adaptable for applications requiring mid-IR frequencies, such as, for example, high resolution spectroscopy and chemical and gas sensing applications.

Reference is now made to FIGS. 1A–1D illustrating various configurations for providing first and second high power optical sources, injection and pump sources, providing first and second wavelengths λ_1 , λ_2 to a nonlinear frequency mixing (NFM) device to produce a third wavelength. In general, the wavelengths, λ_1 , λ_2 , may be near-IR frequencies capable of being produced from high power sources such as semiconductor laser diodes or amplifiers or optical fiber oscillators or amplifiers. These sources can, in turn, be utilized for difference frequency mixing, via an appropriate nonlinear crystal device to produce wavelength, λ_3 , in the mid-IR frequency range between about 2 μm to about 5 μm .

With reference to FIG. 1A, a tunable high power injection source 10 provides a first wavelength beam, λ_1 (or injection wavelength λ_1), and a second fixed high power pump source 12 provides a second wavelength beam, 2, (or pump wavelength λ_p). Sources 10, 12 comprise in this configuration, as well as the other configurations to be discussed, a high power diode laser, such as Model No. SDL-8630, available from SDL, Inc., 80 Rose Orchard Way, San Jose, Calif. 95134, a MOPA device, a semiconductor amplifier and laser combination, or a semiconductor pumped fiber laser or amplifier. Tunable high power injection source 10 may comprise a semiconductor amplifier in combination with an external tuning cavity, such as disclosed in U.S. Pat. No. 5,392,308 to Welch et al., which is assigned to the assignee herein and is incorporated in this disclosure by reference thereto. High power sources 10, 12 are provided so that $\lambda_1 > \lambda_2$. Also, it should be noted that source 12 may be the tunable source and source 10 may be the fixed source.

Beams λ_1 , λ_2 are combined from sources 10, 12 by means of dichroic beam splitter or combiner 14, and the combined beam is provided as input to NFM device 16. Device 16 is a noncritical, single pass, quasi-phase matching (QPM), difference frequency mixing (DFM) device comprising a crystal or waveguide structure made, for example, from such material as LiTaO₃, LiNbO₃, KTP, AgGaS₂ or AgGaSe₂. Device 16 is periodically poled device, as known in the art, which receives the combined beam input, λ_1 , λ_2 , to be

frequency mixed. The output of NFM device 16 generates a frequency mixed beam having an idler wavelength, λ_3 , in the mid-IR range. The idler wavelength, λ_3 (or λ_i) is derived by the difference frequency equation, $\lambda_3 = \lambda_1 \cdot \lambda_2 / \lambda_1 - \lambda_2$.

In application, as indicated above, at least one of the high power sources, such as source 10, is tunable, indicated by arrow 10A, and may have, for example, an tunable wavelength between 775 nm to 900 nm or other wavelength, while the other high power source 12 may have a substantially stable frequency, for example, at 1100 nm. Such a stable frequency source may of the type disclosed in U.S. Pat. No. 5,485,481 to Ventruo et al., which is assigned to the assignee herein and is incorporated in this disclosure by reference thereto. It also may be a monolithic master oscillator power amplifier (M-MOPA) laser diode source similar to SDL Model Number 5760-A6, manufactured by SDL, Inc. of San Jose, Calif. The combined outputs provided to NFM device 16 produce a longer wavelength having a mid-IR frequency in the range of about 2.5 μm to about 5.0 μm .

As is known in the art, periodic nonlinear coefficient patterning of device 16 may be accomplished by titanium indiffusion in LiNbO₃, by proton exchange and anneal, by heat treatment or by electric field induced poling. Other types of periodic nonlinear coefficient patterning may be employed. Periodic nonlinear coefficient patterning may generally be one of at least two different possible patterns or gratings, for example, (1) a periodic poled pattern of positive and negative nonlinear coefficients or (2) a periodic modulated pattern of either first positive or negative nonlinear coefficients and a second nonlinear coefficient of comparatively low magnitude or of zero magnitude, i.e., no nonlinearity. Electric field induced poling is preferably utilized for NFM device 16 because of its accuracy in forming substantially straight wall domain boundaries in the bulk crystal or waveguide material.

The configuration in FIG. 1B differs from FIG. 1A by the fact that both high power sources 10, 12 are independently tunable sources. Because both sources 10, 12 are tunable, it is possible to extend the tunable mid-IR range from between about 2.0 μm to about 5.0 μm . As an example, tunable source 10 (as indicated by arrow 10A) may be tunable within the frequency range of about 730 nm to about 833 nm, while tunable source 12 (as indicated by arrow 12A) may be tunable within the frequency range of about 1000 nm to about 1150 nm. When these sources are selectively tuned and mixed with their combined output provided to NFM device 16, the full range of selected mid-IR frequencies within the range of about 2.0 μm to 5.0 μm is achievable, within the limits, of course, of the particular absorption edge characteristics of the nonlinear crystal.

FIG. 1C illustrates in graphic form the relative relationship between the pump wavelength, λ_p , the signal wavelength, λ_s , and the idler wavelength, λ_i . For a given tuned pump wavelength, λ_p , and tuned signal or injection wavelength, λ_s , such as indicated at "X", an idler mid-IR frequency, λ_i , can be achieved based on a given periodic poled grating of NFM device 16.

The configurations illustrated in FIGS. 1A and 1B can also be additionally wavelength tuned by means of temperature tuning of the NFM device 16. This is accomplished by controlling the application of heat to device 16 through its submount which changes its resultant mixing frequency. Variation in the uniformly applied heat will vary the frequency mixing response of device 16.

The configuration in FIG. 1D is different from the configuration of FIGS. 1A and 1B in that a second source for the

second wavelength beam, λ_2 , is not utilized or necessary. Instead, pumping source 10 having a pumping wavelength, λ_1 , is coupled to NFM device 16 comprising a noncritical, multiple pass, quasi-phase matching (QPM), optical parametric oscillation (OPO) device which may be a crystal or waveguide structure made, for example, from such material as LiTaO₃, LiNbO₃, KTP, AgGaS₂ or AgGaSe₂. In the case here, QPM OPO device 16 functions as an oscillator creating within its optical cavity a second shifted wavelength, λ_2 , which is difference frequency mixed with pumping wavelength, λ_1 , to produce an idler wavelength, λ_3 , in the mid-IR frequency range where $1/\lambda_3 = 1/\lambda_1 - 1/\lambda_2$. QPM OPO device 16 may be also independently wavelength tuned by means of temperature tuning. A heater may be provided at the submount for device 16. Variation in the uniformly applied heat will vary the frequency mixing response of device 16.

Reference is made to FIG. 2 illustrating pumped mid-IR wavelength source 20 which is a detail embodiment for the FIG. 1B configuration. Source 20 comprises two tunable high power diode laser sources 21 and 22, such as high power, single spatial mode tunable laser diode sources, Model No. SDL-8630, available from SDL, Inc., 80 Rose Orchard Way, San Jose, Calif. 95134. The tuned output of these sources, λ_1 and λ_2 , is combined via folding mirror 26 and dichroic beam combiner 27 and provides as input to NFM device 23 which comprises a QPM DFM waveguide device. The output of laser diodes 21, 22 are individually collimated by respective lenses 24 for presentation to half wavelength plates 25 for rotating the polarization axes of the output beams to be aligned when they are combined at beam splitter 27. Lens 24 may be a lens system to correct for astigmatism in the laser source output depending upon the type of laser source employed. Such lens systems are disclosed in U.S. Pat. No. 5,321,718, assigned to the assignee of this application and is incorporated herein by reference thereto. The output of beam splitter 27 is focused to an input face of device or waveguide 23 by means of focusing lens 28. Waveguide 23 is periodic poled crystal of LiNbO₃ having a poled grating period that is adapted to mix the combined wavelengths λ_1 and λ_2 from beam splitter 27. The idler output 31 comprising idler wavelength, λ_3 , in the mid-IR frequency range from waveguide 23 is collimated by lens 29, e.g. a CaF₂ lens. Periodic poled LiNbO₃ in both bulk and waveguide form are known in the art, one such example being discussed in U.S. Pat. No. 5,295,218, incorporated herein by reference thereto. Wavelength discriminating beam splitter 30 may be a Ge filter employed to absorb any remaining near IR wavelengths from sources 21 and 22 that have not mixed in waveguide 23 or a dichroic beam splitter so that beam 31 is substantially a wavelength selected mid-IR frequency which may be used in an IR application as collimated or focused to a spot as required. Mid-IR source 20 may be optimized by employing optical isolators between each of the lenses 24 and plates 25.

An important aspect of this embodiment is that laser diode sources 21, 22 may be selectively tuned to a wavelength in a near-IR frequency range to provide two closely spaced near-IR wavelengths which are at least a 10 nm in wavelength difference so that they can be appropriately mixed in QPM DFM waveguide 23 via an appropriately selected poling period to produce a desired idler wavelength in the mid-IR range. As a specific example, laser diode sources 21, 22 may be respectively tuned to generate a wavelength about 780 nm and about 980 nm to produce a tunable mid-IR wavelength output 31 in the range between about 3.0 μm to 4.5 μm .

LiNbO₃ crystal **23** is periodically poled, preferably employing electric field induced poling, which will be discussed in greater detail later. For example, a grating having a 21 μm period electrode stripes is prepared along the crystal y-direction on the +z face of 0.5 mm thick crystal wafer. With the application of a electric field poling by means of applying electrical pulses, a domain inversion pattern can be created that is 7.8 mm long, having a 40% duty cycle. Thus, with a 21 μm poling period at crystal **23**, tuning the signal laser diode wavelength, λ_2 , between about 958 nm and 990 nm, the pump laser diode has optimal phase matching between about 776.7 nm and 781.1 nm, resulting in a mid-IR tuned wavelength in the range between about 3.6 μm and 4.3 μm , as seen from the data results set forth in FIG. 7. The tuning curve for an output idler power at 3.9 μm for this described arrangement is shown in FIG. 3 for $\lambda_2=972$ nm; pump power, P_p , =250 mW; and signal power, P_s , =530 mW. As indicated above, the pump wavelength range is relatively small, falling between 776.7 nm and 781.1 nm, with FWHM at about 2.2 nm with the signal wavelength tuned at 972 nm. In FIG. 4, the idler power to signal power is shown where the pump wavelength, λ_p , is 777 nm, the signal wavelength, λ_s , is 980 nm, the idler output wavelength, λ_i , is 3.75 μm , and the pumping power is 180 mW. A power of 7.1 μW has been achieved for an idler output wavelength of 3.9 μm . The dependence of the idler power at 3.75 μm on the incident signal power demonstrates a maximum generated mid-IR output power of 6 μW . With 180 mW of pump power, the slope efficiency of the idler power with respect to the signal power is 1.4×10^{-5} , which corresponds to an overall conversion efficiency of 0.008%/W, which corresponds to a material conversion efficiency of 0.015%/W-cm when AR coating are applied to the input and output surfaces of crystal **23**. Higher powers can be generated over a larger range of mid-IR wavelengths by employing a longer LiNbO₃.

These conversion efficiencies are comparable to conversion efficiencies in AgGaS₂ crystals employed as for waveguide **23**. However, AgGaS₂ crystals are more limited in the handling wider ranges of pumping wavelengths compared to LiNbO₃ crystals. In this connection, reference is made to FIGS. 5 and 6 which respectively show the non-critical phase matching characteristics for AgGaS₂ crystals and for periodically poled LiNbO₃ crystals relative to the pump/signal wavelengths versus mid-IR DFM wavelength for a 21 μm poled pattern. Curve A in FIGS. 5 and 6 relates to the signal wavelength, λ_2 , variation and curve B in FIGS. 5 and 6 relates to pump wavelength, λ_1 , variation. It can be seen from these curves that the tunability for LiNbO₃ crystals is superior to that for AgGaS₂ crystals in that comparatively smaller tuning wavelength changes for either or both of the pump or signal wavelength to achieve a fairly broad range of selectable mid-IR wavelengths as previously mentioned. Thus, LiNbO₃ crystals are useful for mid-IR QPM DFM with efficiencies comparable to AgGaS₂ crystals but provide for a much wider freedom of pumping wavelength and greater versatility in wavelength selectability for mid-IR wavelengths, as illustrated in FIG. 7, particularly extending out to the material absorption edge of LiNbO₃ crystals to mid-IR wavelengths at 4.5 μm to 5.0 μm .

The foregoing discussion relative to FIG. 2 has been related to laser diode sources **21**, **22** comprising tunable laser diode sources. Such tunable sources can be of the type that include an external optical cavity with a rotatable reflecting mirror that provides either first order or second order light into an oscillator or amplifier device such as exemplified in U.S. Pat. No. 5,392,308, which is incorporated herein by

reference thereto. Alternatively, these two sources may also be distributed Bragg reflector (DBR) laser diodes having pump and signal or injection wavelengths that are mixed in waveguide **23** to generate over 100 μW of mid-IR at a chosen mid-IR wavelength in the range between about 2.0 μm to 4.0 μm . Such a system **20** can operate at room temperature and can be produced at a lower cost compared to cryogenic mid-IR laser diode systems and, further, is suitable for packaging on a single substrate.

The tunability of DBR laser diodes **21**, **22** may also be accomplished by means of temperature and current tuning, i.e., heating the diodes or varying their current density to cause changes in operating temperature and injection current which in turn causes changes in their wavelength output. This method of wavelength tuning allows for controlled change of the pumping and signal wavelength over several nanometers to produce a mid-IR wavelength at waveguide **23** that is in the range between about 2.0 μm to 4.0 μm . Although the mid-IR range of wavelengths is less than in the case of employing tunable laser diode sources, small range of pump and/or signal tunability provides a comparatively large mid-IR wavelength range of tunability when employing LiNbO₃ crystals, as based upon the data shown in FIGS. 5 and 6.

Reference is now made to FIG. 8 which illustrates a more detailed system of the FIG. 1D configuration comprising a pumped mid-IR wavelength source **32**. Here, only one laser diode source, i.e., pumping source **33**, at wavelength, λ_1 , is required since the mixing signal wavelength is generated in the QPM OPO waveguide **35** which functions as an oscillator via high reflecting (HR) input/output deposited or coated surfaces **36A** and **36B**, internally generating a second wavelength, λ_2 , while mixing with the pumping wavelength, λ_1 , to produce an idler wavelength, λ_3 , at **37**. The parametric gain at the second wavelength, λ_2 , must be balanced with the losses due to the necessary output reflectivity and internal losses of the resonator of OPO waveguide **35**. The condition for parametric oscillation threshold is given by the equation,

$$\eta P_p L = 2[\alpha L + \ln(1/R)],$$

where η is the normalized conversion efficiency, P_p is the pump power, L is the length of the waveguide, α is the linear loss, n is the refractive index of LiNbO₃, and R is the reflectivity of the mirrors **36** at the second wavelength, λ_2 . Typical parameters are $L=1$ cm, $\alpha < 0.05$ cm⁻¹, $\eta=0.015\%$ /W-cm with reflective coatings **36A** and **36B** of $R=98\%$, the pumping power required is approximately 1 W. The OPO threshold power can be further reduced by a factor of two by reflecting the pumping power exiting from output **37** of waveguide **35** back into the waveguide with an appropriate external resonator mirror, in lieu of mirror **36B**, to reflect the pumping wavelength, λ_1 , back into the device optical cavity. However, such a resonator mirror is transparent to the idler wavelength, λ_3 .

The structure of pump source **33** comprises a monolithic master oscillator power amplifier (M-MOPA) comprising a flared amplifier **33A** and a master oscillator **33B** with cavity Bragg reflectors **33C**. Master oscillator may be slightly tapered away in the direction away from flared amplifier **35A**, which concept is disclosed, in part, in U.S. Pat. No. 5,392,308, except that the slight taper in oscillator **33B** in the case here extends from rear facet to the inner end of flared amplifier **33A**. The slight taper is shown exaggerated in FIG. 8. The purpose of the slight taper, which may be a few degrees, e.g., one to eight degrees, from the axial alignment of the optical cavity, is to provide for good coupling of light

into flared amplifier 33A and to increase the beam divergence in this region while still providing good waveguiding properties in oscillator 33B.

The structure of waveguide 35 may be identical to the structure of waveguide 23 in FIG. 2 except, as previously indicated, waveguide 35 is provided with reflecting surfaces to function as an oscillator. The QPM LiNbO₃ waveguides are provided with an alternated, poled pattern 38 which is thereafter provided with a waveguide stripe region 39 functioning as a waveguide for propagating radiation provided as input at HR surface 36A, and is formed by an annealed proton exchange resulting in high conversion efficiency for mid-IR wavelengths compared to the use of bulk ferroelectric waveguides. The tight confinement of the interacting modes of the lightwaves increases the intensity as well as the nonlinear conversion efficiency in waveguide 39.

Moreover, a further improvement of the conversion efficiency of the waveguide region 39 can be realized by reducing the refractive index asymmetry of this region. The annealed proton exchanged stripe 39 provides for a higher index region for the propagating light compared to the bulk LiNbO₃ cladding material ($n=2.2$) below the guide and air ($n=1$) for the upper cladding. This asymmetry of the waveguide region 39 requires forming a deep buried proton exchange in order to adequately support the generation of mid-IR modes generated by the difference frequency mixing (DFM) and resulting in a waveguide that supports many modes at shorter near-IR wavelengths of the pumping source. This strong guiding support is because of waveguide region 39 providing for a more symmetric refractive index profile and, consequently, a more efficient nonlinear frequency conversion.

In the case of frequency conversion for DFM where there is a large difference between the pump and idler wavelengths, waveguide 35 must be designed so that the longer idler wavelength radiation can be efficiently guided. When this situation is achieved, the waveguide is typically multimode at both the pump and signal wavelengths. For every triplet of modes, there is a unique phase-matching period and conversion efficiency, the latter of which is calculated from the field profiles for each mode. From these calculations, it has been determined that there may typically be over twenty guided modes at the pump wavelength and six guided modes at the signal wavelength. Since only one mode pair phase matches to generate a mid-IR idler wavelength, the conversion efficiency is reduced to roughly 1 over 100 of the theoretical maximum because the power from the input beams from the laser diode source is split into many modes that can be formed in the waveguide region 39 with little discrimination in their coupling.

The combination of this multi-mode generation and the additional reduction in frequency conversion efficiency brought about by poor modal overlap are due to the asymmetrical waveguide having cladding regions with unequal indices.

As shown in FIG. 9, a cross section of a LiNbO₃ waveguide 40 is shown which comprises bulk crystal region 41 within which is formed waveguide region 42, and over which is formed LiNbO₃ cladding region 43. As a result, waveguide region 42 for propagating radiation is formed below the surface of the waveguide structure so that it is possible to eliminate the potential cutoff of longer wavelength idler modes while maintaining all three wavelengths (pump, signal and idler) within waveguide 42 nearly single mode, as graphically indicated in FIG. 9 by the mode waveforms, wherein the three modes are substantially symmetrical within waveguide 42. With buried waveguide

region 42 being more symmetrical, the waveguide modes will be fewer and more substantially overlap each other yielding a higher normalized conversion efficiency. By utilizing the optimized buried waveguide shown in FIG. 9, normalized conversion efficiencies of at least about 25%/W for a 1 cm crystal can be achieved, which is about two orders of magnitude higher than that attainable with bulk crystal phase matching.

Cladding region 43 in FIG. 9 is fabricating by following the annealed proton exchange process to reverse exchange lithium for hydrogen in the upper portion of formed waveguide region 42 creating a lower index region 43 above waveguide region 42. The process is carried out as follows. First, domain inversion pattern, such as pattern 38 in FIG. 8, is performed by patterning a layer of titanium on a LiNbO₃ wafer surface. Next, the pattern is diffused into the crystal by means of furnace annealing, utilizing a diffusion temperature near the crystal Curie temperature. Next, a deep proton exchange profile is formed by proton exchange in molten benzoic acid followed by annealing. Next, the upper surface region of the formed waveguide is subjected to reverse exchange to bury the proton exchanged LiNbO₃ waveguide. This is accomplished by introducing Li ions into the surface region by means of a melt mixture of KNO₂:NaNO₃:LiNO₃ in the ratio, for example, of about 1:1:0.1 which is applied to the surface of the formed waveguide. The KNO₂/NaNO₃ mixture functions as carrier for the LiNO₃ and the mixture is heated to near their eutectic point of the mixture which is lower than the melting point of the incorporated nitrates per se. In spite of the use of high temperatures, there is no damage to the underlying proton distribution in waveguide 42 below this surface treatment since the restoration of surface cladding region 43 occurs in a short period of time compared to the initial anneal proton exchange process used to form waveguide 42.

An alternative approach to forming buried LiNbO₃ waveguides is overcoating the waveguide surface with a dielectric material index matched to bulk LiNbO₃, e.g., by depositing a dielectric film or by optical contacting of a polished z-cut LiNbO₃ wafer portion to the waveguide surface. Such a dielectric film will need to be fairly thick, such as around 1 μ m, and very accurately matched to the refractive index of LiNbO₃ to substantially reduced the number of modes in the waveguide. Optical contacting with another LiNbO₃ wafer portion requires careful surface preparation. As a further alternative, the Li reverse exchange region 43 may be overcoated with a dielectric coating material having a refractive index accurately matched to the refractive index of LiNbO₃.

An alternative approach to forming the periodic poling by means of titanium diffusion is electric field poling to achieve QPM. Electric field poling is accomplished by depositing a periodic pattern of conductive electrodes or the use of planar liquid electrodes on an insulative periodic pattern formed on either the +z axis or -z axis surface of the LiNbO₃ crystal, having a period that matches the QPM period. After the electrode patterns are applied to these surfaces, then high voltage pulses are applied across the electrode sets, domain reversal occurs in regions of the applied high voltage pulses. The range of the applied electric field falls with several kV per cm to several 100 kV per cm. Domain reversal occurs through the entire crystal wafer so that substantially straight, vertical domain boundaries in the z plane are obtained so that the full crystal volume can be employed for nonlinear interaction. The patterned high voltage field is applied at room temperature across the crystal. The processing of E-field poling is disclosed in the articles of Jonas Webjorn et

al., Quasi-Phase-Matched Blue Light Generation in Bulk Lithium Niobate, Electrically Poled via Periodic Liquid Electrodes, *Electronic Letters*, Vol. 30(11), pp. 894–895, May 26, 1994 and “Electric Field Induced Periodic Domain Inversion in Nd³⁺-Diffused LiNbO₃”, *Electronic Letters*, Vol. 30(25), pp. 2135–2136, Dec. 8, 1994, and L. E. Myers et al., Quasi-Phase-Matched 1.064-μm-Pumped Optical Parametric Oscillator in Bulk Periodically Poled LiNbO₃, *Optics Letters*, Vol. 20(1), pp. 52–54 (Jan. 1, 1995), which are incorporated herein by reference thereto.

A DFM rare earth doped, periodic poled nonlinear crystal material functioning as rare earth doped oscillator may be employed using the waveguide architecture of device 35. In this case, a single laser diode pump source provides wavelength, λ₁, and device 35 would be a rare earth doped nonlinear material, such as LiNbO₃ or KTP doped with Er³⁺, Nd³⁺, Yb³⁺, Pr³⁺, or Tm³⁺, and is periodically poled, such as by means annealed proton exchange, titanium diffusion or E-field poling. Rare earth doped oscillator 35 is provided with reflectors 36A and 36B at the input and output surfaces or may have reflectors positioned in an external optical cavity forming an external resonator. The input pump beam is partially converted to a longer wavelength by pumping the rare earth doped oscillator. The unabsorbed pump radiation wavelength within the rare earth doped oscillator 35 then difference frequency mixes within the crystal with the internally generated longer radiation wavelength to generate even longer radiation wavelength. The generated longer wavelength is internally reflected within the crystal due to the reflector coatings, which are chosen to provide high reflectance for such longer wavelengths. The periodic poling period is chosen so as to quasi-phase match the DFM interaction. Examples of representative wavelength interactions for mid-IR wavelengths, for example, useful in spectroscopy are shown in Table 1 below.

TABLE 1

| Dopant | Pumping Wavelength, λ ₁ , Range | Rare Earth Doped | |
|------------------|--|-----------------------------------|--------------------------|
| | | Lithium Niobate Lasing Wavelength | Mid-IR Wavelength Output |
| Nd ³⁺ | 805 nm–810 nm | 1060 nm | 3.3 μm–3.4 μm |
| Yb ³⁺ | 910 nm–920 nm | 1120 nm–1150 nm | 4.3 μm–5.2 μm |
| Tm ³⁺ | 1120 nm–1200 nm | 1600 nm | 3.7 μm–4.8 μm |
| Er ³⁺ | 980 nm | 1520 nm–1580 nm | 2.6 μm–2.8 μm |
| Pr ³⁺ | 1010 nm–1020 nm | 1290 nm–1330 nm | 4.2 μm–4.4 μm |

Reference is now made to the embodiment shown in FIG. 10 comprising a pumped mid-IR wavelength source 50, which is an example of the FIG. 1A configuration. Source 50 comprises a cw or modulated signal source 51 with a substantially fixed wavelength output, a tunable pumped source with an adjusted wavelength output, and a NFM device that also provides for wavelength tuning. This wavelength tuning may be accomplished by changing the effective poling period of the nonlinear device by means of stage translation of the crystal laterally of the input beam path or by temperature tuning of the NFM device 16 by means of applying heat to the submount of the device. Transverse translation can be accomplished either by minute servo translation of the crystal in a path perpendicular to the axis of the input beam or by slight rotation of the crystal relative to the axis of the input beam.

In particular source 50 comprises a tunable laser source 51 which has, together with necessary optics 51C and mirror surface 51D, an external cavity with a rotatable mirror 51A for selecting a particular wavelength, λ₁, under lasing conditions in conjunction with associated gain element 51B

comprising a semiconductor amplifier, e.g. a flared gain section 51G of the type disclosed in U.S. Pat. No. 5,392,308 with appropriate output optics 51E. As an example, tunable laser diode 51 may have a tunable wavelength, λ₁, range between 775 nm and 900 nm providing an output of about 1 W. Fixed diode laser source 52 comprises a monolithic master oscillator power amplifier (M-MOPA) having a gain section 52A providing feedback by means of DBRs 52D, a modulator section 52B for providing frequency or pulse modulation, and a flared or tapered amplifier section 52C for providing high gain providing a collimated output via appropriate output optics 52E. For amplitude modulation, modulator section 52B would not be employed or would be eliminated. As an example, M-MOPA 52 may have an output wavelength, λ₂, of about 1000 nm to 1100 nm providing output power at 1 W. Wavelength beams, λ₁, λ₂ are combined by dichroic beam combiner 53 and are presented as a focused beam input, via lenses 55, to NFM device 54.

Because M-MOPA 52 has an integrated phase modulator, the DFM source 50 has particular application for highly sensitive FM spectroscopy. The stable spectrum and single diffraction limited spatial mode output from both high power, near-IR laser sources 51 and 52 results in high conversion efficiency and narrow linewidth mid-IR wavelengths.

NFM device 54 is a QPM DFM crystal, e.g., LiNbO₃, with a periodic poled pattern 59 formed on its +z surface by, for example, electric poling, as previously explained. However, the formed pattern is in a fan-shape about an arc that has a center of origin to left of the plane of FIG. 10 so that poled pattern 59 is fanned out toward the right of FIG. 10 with equally spaced, reversed poled domains. The periodic domain inversions of pattern 59 may be, for example, of 0.5 mm widths and the period of inversion may increase by 1 μm in the -y direction due to the fanning out of the domains. Periodic poling of the LiNbO₃ crystal is preferably accomplished by means of electric field poling in the manner as previously explained because this type of poling is best suited for forming fan shaped electrodes in order to carry out the poling process. The domain inversions extend from top to bottom between the z crystal faces and the width of the poling period varies slowly along the x axis of the crystal. As an example, the periods or the crystal may vary from about 20 μm to 24 μm along the x axis. Upon crystal lateral translation in the x direction, indicated by arrow 58A, by means of servo motor control 58, generating mid-IR wavelengths between about 2.6 μm to 4.4 μm, given the adjusted and fixed wavelengths λ₁, λ₂ and possibly limited at the longer wavelength end of the mid-IR range spectrum by material absorption edge. However, by translation of crystal 54 perpendicular to the beam propagation path, i.e., the crystal x direction, by means of servo motor control 58 in combination with the wavelength tuning of the pumping wavelength via only one of the laser sources 51, phase matching can be achieved over a broader range of mid-IR frequencies, i.e., between about 2.6 μm to 5.0 μm. This is an important aspect of this invention in that tuning range requirements in utilizing a near-IR pump laser is greatly narrowed in covering a broad mid-IR range of selectable wavelengths, particularly when compared to noncritical birefringent phase matching where both wavelength inputs must be tuned together.

Frequency mixing occurs within device 54 so that at its output, via Ge filter 57, is a mid-IR wavelength within the tunable mid-IR range of about 2.6 μm to 5.0 μm based upon the above mentioned pump and signal wavelengths, λ₁, λ₂. Ge filter 57 absorbs any remaining, unmixed near-IR wavelengths and is transparent to the mid-IR wavelengths, λ₃.

As a specific example, a tunable laser pump source **51**, such as Model No. SDL-8630, may be utilized having a tunable frequency range of 770 nm to 790 nm at 330 mW output. M-MOPA signal device **52** may have a wavelength of 1013.3 nm with a power output of 625 mW and with source **51** tuned at 779.8 nm with output power at 325 mW, the peak of the tuning curve across the pump wavelength band generates a mid-IR idler wavelength, λ_3 , from crystal device **54** of 3.38 μm with FWHM equal to 1.1 nm. Device **54** in the case here has an adjusted 21.1 μm poling period and is at 23° C. The actual poled interaction length was 11 mm. The frequency conversion efficiency from near-IR to mid-IR wavelength was 0.011%/W, and a peak power of 22 μW was generated at 3.38 μm . Correcting for Fresnel reflections, the actual frequency conversion efficiency in crystal device **54** was 0.017%/W. By translating device **54** perpendicular to the beam propagation direction, phase matching was obtained at wavelengths between 3.34 μm and 3.57 μm . The poling period varies, via such lateral translation in the x direction, from 21.0 μm to 21.5 μm for achieving these mid-IR wavelengths. It should be understood that the upper mid-IR wavelength was limited in this particular example by the tunable capability of laser source **51** so that longer mid-IR wavelengths can be achieved with a source **51** having longer tunable wavelength capability.

As previously indicated, temperature changes to device **54** can be effectively applied to generate different mid-IR wavelengths. The phase matching wavelength for changes in wavelength at source **51** changes with changes in the temperature of device such that the generated mid-IR wavelength for each 0.1 μm change in the poling period is 0.046 μm . Continuous tuning by non-critical phase matching over the mid-IR range can be achieved by temperature tuning over the employment of only a 30° C. temperature range. As an example, using a poling period at 21 μm with a signal wavelength at 1013.3 nm where $d\lambda/dT$ is equal to 0.00155 $\mu\text{m}/^\circ\text{C}$., at 23° C., the mid-IR wavelength was about 3.34 μm ; at 40° C., the mid-IR wavelength was about 3.365 μm ; and at 55° C., mid-IR wavelength was about 3.39 μm .

FIGS. **10A** and **10B** show alternative forms of changing the effective poling period of device **54**. In FIG. **10A**, NFM device **54** is rotated about a central axis **54'**, as indicated by arrow **54R**, to change the effective poling period of domains **54"**. Alternatively, the axis of rotation need not be central, but can be slightly offset from central axis **54**. Also, an effective linear change of the nonlinear period of device **54** can be accomplished by slight rotation of device **54** in z direction about axis **54'** concurrently with rotation the of device **54** in the y direction about an axis perpendicular to axis **54'**. In FIG. **10B**, NFM device **54** comprises a plurality of parallel waveguide stripes or regions **54A–54D** each with a different pattern pitch. For example, the period for section **54A** may be 20 μm , for section **54B** may be 21 μm , section **54C** may be 23 μm and section **54D** may be 24 μm . Device **54** is laterally translated by servo motor control **58** to align any one of sections **54A**, **54B**, **54C** and **54D** within the optical path of input beam of wavelengths λ_1 , λ_2 . The poling patterns of FIG. **10B** have been exaggerated for purposes of illustration. It is preferred that the pattern of periods of FIG. **10B** be formed by means of electric field poling since this process can be easily applied to such a structural arrangement except that, in this case, the electrode pattern is formed as a plurality of electrode rows of different pitch on both z faces of the crystal device **54**.

Reference is now made to FIGS. **11** and **12**, which illustrate another embodiment for either the FIG. **1A** or FIG. **1B** configuration, comprising mid-IR wavelength source **60**

utilizing a high power, laser source pumped, double-clad fiber amplifier **69** which provides a high power beam at wavelength, λ_1 , to NFM device **64**.

An example of the type of optical double clad fiber useful for fiber amplifier **69** is illustrated in cross section in FIG. **12**, although other double clad configurations may easily be employed. Fiber **69A** comprises a core **69B**, inner cladding **69C** and outer cladding **69D**. Core **69B** may be a single mode fused silica core having a diameter of 5–6 μm and may be doped or co-doped with rare earth ions, such as Nd^{3+} , Yb^{3+} or Er^{3+} . Core **69B** is surrounded by substantially rectangular shaped undoped silica inner cladding **69C** which, in turn, is embedded in a low refractive index polymer outer cladding **69D**. This configuration allows for a large numerical aperture of up to 0.6 for pump radiation captured by polymer inner cladding **69C**. The rectangular geometry fosters maximum overlap of propagating modes in inner cladding **69C** with doped core **69B**. By coupling the radiation from high power, multimode laser diode pump source **65** into inner cladding **69C** and the radiation from single mode injection source **66A** into core **69B**, double-clad fiber **69A** functions as a high power amplifier, preserving the temporal and spectral properties of the injection or signal source beam in a single spatial mode output to NFM device **64**. As an example, double-clad fiber amplifier **69A** doped with Nd^{3+} may provide an output at 1.06 μm , or doped with Yb^{3+} may provide an output at 1.1 μm , or doped with Er^{3+} may provide an output at 1.55 μm . Such near or low end IR generation would improve the frequency conversion efficiency for longer mid-IR output from NFM device **64**, such as above about 4.4 μm , which is approximately the absorption edge for LiNbO_3 , dependent upon its optical properties. Also, the output beam from amplifier **69A** is highly stable over time, can operate under adverse operating conditions, and has a near Gaussian, diffraction limited mode with M^2 measured at approximately 1.1 which is better than that achievable from rod or YAG lasers. The availability of this large pumping bandwidth removes many constraints on the operating temperature of laser source **65A**, resulting in a more efficient and compact system. In addition, the large pump bandwidth of Yb^{3+} doped fibers permits the use of wavelength multiplexing of pump lasers for high power efficient operation of double clad fibers. Moreover, the pumping bandwidth of fiber amplifier **69A**, particularly Yb^{3+} doped fibers, is much broader than possible from diode pumped rod or YAG lasers. Lastly, the fiber geometry of FIG. **12** provides long propagation distance for absorption of the pump light resulting in high absorption of the pump beam even if the wavelength of the pump beam is slightly off of the gain peak of the rare earth doping of fiber amplifier **69A**. Referring again to FIG. **11**, mid-IR wavelength source **60** comprises high power injection source **61** for providing a high power, fixed pumping near-IR wavelength, λ_1 , which is combined with another near-IR wavelength, λ_2 , from tunable pump source **62** via dichroic beam combiner **63** for input to NFM device **64**. In this connection, the configuration of FIG. **11** is substantially similar to the configuration of FIG. **1A** except for the application of source **61**. If pump laser source **65A** in injection source **61** is changed to a tunable source, such as device **51** in FIG. **10**, then the configuration of FIG. **11** would be substantially similar to the FIG. **1B** configuration where pump source **62** is also a tunable source.

Injection source **61** comprises multimode pump laser **65A** for providing wavelength, λ_p , which is combined, via beam combiner **67A**, with the output from injection laser diode **66A**, which may be cw or pulsed, providing injection

wavelength, λ_T . As an example, pump laser 65A may be comprise a of a high brightness, quasi-cw laser diode bar, and injection laser 66A may be a DBR laser diode having a gain peak near that of rear-earth doped fiber 69A. A diode bar for source 65A provides a multiplicity of pump sources, such as 16 or more per bar and the possibility of employing multiple such bars, so that failure of any one or more laser elements in one or more bars does not affect the other operating laser elements or the resulting efficiency of fiber amplifier 69A. As an example, pump source 65A may be a 17 W fiber coupled laser diode bar. Pump source 65A at wavelength, λ_P , is coupled into the inner cladding 69C of fiber amplifier 69A while injection laser source 66A at wavelength, λ_1 , is coupled into core 69B of fiber amplifier 69A. The injected wavelength is optically coupled, via optical isolator 68, into the core 69B of high power, double-clad rare earth doped fiber amplifier 69A, e.g., a Nd doped double clad fiber.

Pulsed operation of pump source 65A and/or injection source 66A allows a larger pulse energy to be extracted from fiber amplifier 69A in comparison to cw operation. The output of fiber amplifier 69A provides a high power beam at wavelength, λ_1 , e.g., in the range of 1.0 μm to 2.0 μm with cw output power as high as 30 W peak power (in the case of double-clad Nd³⁺ doped fiber), or pulsed peak powers of 1 kW or more with pulse frequencies from 100 Hz to greater than 1 GHz. Further increases in power are easily achieved by employing multiple pump sources optically coupled into double-clad fiber amplifier 69A by spatial wavelength and/or polarization multiplexing. By using multiple pump sources, output powers of 10's of watts of average power are possible from a single fiber amplifier 69A.

By pulsing injection laser 66A to a high peak power and low duty cycle, high peak power pulses, such as 1 kW or more, are obtained at the output of double-clad fiber amplifier 69A and injected into NFM device 64 which may be a QPM DFM device, or may be a QPM OPO device, eliminating the requirement of laser source 62 in this latter case. Tunable injection laser source 62 may be pulse modulated.

In the embodiment of FIG. 11, fiber amplifier 69A may, alternatively, be a Raman or Brillouin amplifier requiring no rare-earth doped fiber.

While the foregoing principal embodiment makes preferred use of a high power injection source 61 because of the large power output that it provides for high power applications required for operating NFM devices 64, other high power laser diodes, diode arrays or diode bar arrays may be used in place of injection source 61 if they provide sufficient output power for mid-IR conversion requirements, such as a power output of at least 200 mW.

Reference is now made to other examples for the configurations for high power injection source 61 which are shown in FIGS. 13 and 14. In FIG. 13, high power injection source 61 comprises a double clad rare-earth doped fiber laser 69B having a feedback mechanism in the form of gratings 69G to bring about lasing conditions. Other components of source 61 are similar to FIG. 11 and the description there is equally applicable to the components here comprising multimode pump laser source 65B. An additional injection laser source 66B, shown in dotted line may possibly be provided, via a beam combiner 67B for example (also shown in dotted line), with its output optically coupled into fiber laser 69B in order to narrow and stabilize the lasing wavelength band to improve the nonlinear frequency mixing conversion efficiency.

Reference is made to FIG. 23 relative to mid-IR wavelength source 150 which is a modification of the high power

injection source 61 of FIG. 13. FIG. 23 is the same except that fiber laser 69B is wavelength tunable. As shown in FIG. 23, gratings 69G include wavelength tuning devices 69T. In the case here, a tuning device 69T is shown for each grating although it is possible to employ only one such device. Tuning devices 69T change the properties of the gratings 69G so that the wavelength, λ_1 , in oscillator 69B is changed in order to extend the possible range of mid-IR frequencies that can be generated by device 64. Tuning devices 69T may wavelength tune gratings 89G by stretching the fiber grating (U.S. Pat. No. 5,007,705 to Morey et al.); by compression of the fiber grating (U.S. Pat. No. 5,469,520 to Morey et al.); by thermal variation of the grating (U.S. Pat. No. 5,159,601 to Huber); by employing a piezoelectric transducer (U.S. Pat. No. 5,446,809 to Fritz et al.); by mechanically bending the grating fiber, or rotating the grating relative to the fiber or moving the grating relative to a side-polished region of the fiber (see patents of Sorin et al., such as U.S. Pat. No. 5,058,997); and by opto-electric effect by application of an applied electric field across the grating wherein increasing voltage of the field, such as a negative voltage, causes an increase in the refractive index only in the UV exposed regions forming the grating, shifting the grating reflectivity to longer wavelengths (T. Fujiwara et al. in the paper entitled, "UV-Excited Poling and Electrically Tunable Bragg Gratings in a Germanosilicate Fiber", Postdeadline Paper, pp. PD6-1 to PD6-5, *Optical Fiber Conference '95*, (February, 1995). The patents to Morey et al., Huber, Fritz et al. Sorin et al., and the paper of T. Fujiwara et al. are incorporated herein by reference thereto. An additional injection laser source 66B, shown in dotted line may possibly be provided, via a beam combiner 67B for example (also shown in dotted line), with its output optically coupled into fiber laser 69B in order to narrow and stabilize the lasing wavelength band to improve the nonlinear frequency mixing conversion efficiency.

In FIG. 14, high power injection source 61 comprises a semiconductor amplifier 69C having a tapered gain section 69F producing, for example, a power output greater than 1 W providing for tens to hundreds of milliwatts of near-IR wavelength radiation for frequency mixing.

Any one of the high power sources 61 shown in FIGS. 11, 13 and 14 may be employed in groups, such as in tandem and all optically coupled into the NFM device to increase the power input and efficiency of operation of the NFM device. Also, different of such sources, shown in these respective figures, particularly having tunable capabilities to maintain the same wavelength, λ_1 , may be also employed in such groups. As grouped, this combined source can be employed with respect to any of the embodiments illustrated herein.

FIG. 15 discloses a mid-IR wavelength source 70 utilizing a high power injection source 61 of any one of FIGS. 11, 13 and 14 in combination with a NFM device comprising a QPM OPO device 74. Mid-IR generation based on OPO is a desirable approach because only a single high power source 61 is required and mid-IR average power outputs greater than one watt with broad tunability over a 2.0 μm to 4.0 μm wavelength range are possible. The beam output of source 61 at a fixed or tuned wavelength, λ_1 , is optically coupled into OPO resonator 74 via lens system 71 which collects and collimates the beam output from source 61 and focuses the beam as input into OPO device 74. OPO device 74 comprises a periodic poled, bulk LiNbO₃ crystal 72 for noncritical phase matching any one of tuned wavelengths, λ_1 , provided from source 61. QPM OPO device 74 includes external cavity focusing mirrors 73 and 75 wherein mirror 73 is transparent to wavelength, λ_1 , but highly reflective of

internally developed near-IR wavelengths, λ_2 , created within crystal **72** due to frequency mixing, while mirror **75** is transparent to developed mid-IR wavelengths, λ_3 , and highly reflective of internally developed wavelength, λ_2 , created within crystal **72** due to frequency mixing and partially of wavelength, λ_1 . Frequency mixing results in the development of mid-IR wavelength, λ_3 , radiation beam from QPM OPO device **74**.

As in the case of QPM DFM device **54** in FIGS. **10**, **10A** and **10B**, the poling period can be varied laterally across the width of the crystal in the y direction through proper formation of the poling electrodes, such as by electric field poling. By translating crystal **72** perpendicular to the pump beam of wavelength, λ_1 , the mid-IR wavelength from OPO device **74** can be tuned over a broad range of wavelengths, e.g., 2.5 μm to 4.5 μm .

Reference is now made to FIG. **16** discloses the application of a rare earth, single mode, polarization maintaining fiber laser **82** pumped with high power pump source **61** of any one of FIGS. **11**, **13** and **14** or with a lower power single spatial mode diode at 100 mW to 200 mW for frequency mixing in mid-IR wavelength source **80**. Fiber laser **82** may be polarization maintaining so that both unabsorbed pump radiation and oscillator generated radiation have the same polarization. Polarization maintaining features are provided directly in the fiber **82**. Examples of such features are discussed in greater detail below in connection with FIG. **21**. Laser **82** includes Bragg gratings or other fiber reflectors **81** and **83** provided in each end of the fiber. Reflector **81** has high reflectivity of generated wavelength, λ_2 , with low reflectivity at pump wavelength, λ_1 ; reflector **83** has high reflectivity of wavelength, λ_2 , but sufficiently lower than at reflector **81**, to provide for efficient output coupling to NFM device **84**, and has low reflectivity for pump wavelength, λ_1 . NFM device **84** is periodically poled for QPM and may be bulk or waveguide LiNbO₃, KTP or other appropriate non-linear material. Input pump beam at wavelength, λ_1 , is partially converted to a longer wavelength, λ_2 , in pumping rare earth doped fiber laser **82**. The output from fiber laser **82** is then mixed in NFM device **84** to produce the desired mid-IR wavelength, λ_3 . Fairly critical features for efficient DFM in NFM device **84** are the characteristics in the input beam from fiber laser **82** to have narrow linewidth and proper linear polarization. The fiber comprising fiber laser **82** should also be a single spatial mode fiber for both the pump and lasing wavelengths λ_1 and λ_2 , so that the two output wavelengths have a similar spatial distribution and can be easily coupled to or focused into NFM device **84** such as by means of butt coupling or by a lens system.

An example of a system **80** for generating a mid-IR wavelength, λ_3 , near 4.3 μm , which may be used in carbon dioxide sensing, comprises a fiber laser **82** with single mode silica fiber doped with Yb. The fiber has grating regions **81** and **83** to insure lasing near 1155 nm and is polarization maintaining and single mode at both of its oscillating wavelength, λ_2 , e.g., 1155 nm, as well as at the pump wavelength, λ_1 , of high power pump source **61**, which may have a wavelength near 910 nm. The laser output from fiber laser **82** has a narrow linewidth typically around 1 GHz, and is in the same polarization state as the unabsorbed pump radiation.

Representative frequency conversion efficiencies of absorbed pump light to output radiation at 1155 nm is within the range of about 60% to 70%.

For low power mid-IR generation, it is only necessary to convert a small amount, such as a few per cent, of the pump radiation into the longer wavelength, λ_2 , generated by fiber

laser **82** before mixing in device **84**. Several rare earth doped fiber lasers may be employed in tandem or in parallel each with its high power pump source **61** to provide access for different spectral regions of mid-IR wavelengths thereby covering the entire mid-IR range. The fiber dopants that may be employed in one or more of such parallel coupled fiber lasers **82** may be Nd³⁺, Yb³⁺, Tm³⁺, Er³⁺, and Pr³⁺. Representative wavelength interactions for mid-IR spectroscopy are shown in Table 1 above.

As an alternate embodiment, fiber laser **82** may be co-doped with Er:Yb. The Er:Yb single mode fiber may be pumped with a tunable pump source **61** at 1.06 μm and provide an output λ_3 of around 1.55 μm with a 50 nm tuning range. The tuning range can be created by source **61** having an external tuning device **61** shown in FIG. **10** or by using an external tuning device with laser **82** such as illustrated at **104** in FIG. **18**. Both the 1.06 μm and 1.55 μm beams from laser **82** are employed in device **84** for mid-IR generation. Device **84** may also be either a QPM DFM device or a QPM OPO device.

Devices using Raman scattering or Brillouin scattering may be used in combination with high power source **61** for generating the second mixing wavelength, λ_2 , such as the Raman lasers illustrated in FIGS. **17–20**. Laser sources based upon Brillouin scattering are very similar to sources based upon Raman scattering except that Brillouin scattering is based on nonlinear interaction with acoustic phonons whereas Raman scattering is based on nonlinear interaction with optical phonons, these different phonons having different wavelength spacing. In the discussion here, reference will be made generally to Raman lasers using Raman wavelength shift to derive the second wavelength.

Also, in connection with the embodiments of FIGS. **17–20**, multiple outputs from Raman or Brillouin lasers or amplifiers can be utilized as a combined input to a NFM device.

In FIG. **17**, mid-IR wavelength source **90** employs a Raman laser **92** having multiple sets of Bragg gratings to provide for sequential Raman phase shift orders via grating pairs **91**, **93**, **95** to produce wavelength, λ_2 , with a sufficiently different wavelength from wavelength, λ_1 , for mixing together in NFM device **94**. As an example, three to five orders of phase shifting may be employed. Pump light at wavelength, λ_1 , is provided from high power source **61** as input to Raman laser **92** to produced a second wavelength, λ_2 , due to Raman wavelength shifting within laser **92**. This wavelength shifting is accomplished in steps wherein the Raman shift may be represented by $\Delta\lambda$. Grating pairs **95** provide for a first shifting of $\lambda_1 + \Delta\lambda$ producing a first intermediate wavelength. Grating pairs **93** provide for a second shifting of $\lambda_1 + 2\Delta\lambda$ producing a second intermediate wavelength. Grating pairs **91** provide for a third shifting of $\lambda_1 + 3\Delta\lambda$ producing a finally shifted wavelength, λ_2 . In this connection, grating **91**, immediately adjacent to NFM device **94**, has low reflectivity at wavelength, λ_2 , as well as wavelength λ_1 . The typical wavelength shift in Raman oscillator **92** for each wavelength shift order may be in the range of 50 nm to 70 nm. Also, there may be up to five orders of phase shifting employing five pairs of gratings to achieve sufficiently large difference in wavelengths, λ_1 , λ_2 , to achieve frequency mixing in NFM device **94**. NFM device **94** may be of same design as in the case of NFM device **64** in FIGS. **11**, **13** and **14**.

Mid-IR wavelength source **100** shown in FIG. **18** is identical to the embodiment shown in FIG. **17** except that source **100** is wavelength tunable with the inclusion of dichroic beam combiner **102** in the beam path from high

power source **61** which is transparent to wavelength, λ_1 , but is designed to reflect the second intermediate wavelength developed from Raman laser **92** into an external cavity that includes tuning mirror **104** which may be rotated to change the selected output wavelength, λ_2 , of laser **92** for input to NFM device **94**. In this case, grating **91** that is immediately adjacent to NFM device **94** is designed to have low reflectivity at any tuned wavelength, λ_2 as well as wavelength, λ_1 .

Reference is now made to FIG. **19** illustrating mid-IR wavelength source **110** comprising high power pump source **61** coupled to a polarization maintaining, single mode fiber oscillator **112** for Raman wave shifting a portion of the radiation beam at wavelength, λ_1 , from the pump source to a second wavelength, λ_2 , e.g., a single mode fiber with Bragg gratings **111** and **113** for Raman wavelength shifting. The combined outputs at wavelengths, λ_1 and λ_2 , from Raman fiber oscillator **112** is provided as input to NFM device **114**, e.g., QPM DFM or QPM OPO devices. Output beam from high power pump source **61** is injected into silica fiber **112** wherein gratings **111** and **113** are around the peak wavelength of the Raman gain for the fiber. Typical wavelength shifts in Raman oscillator **112** are in the range of about 50 nm to 70 nm. Multiple Raman orders for larger wavelength shifts have already been described in conjunction with FIGS. **17** and **18**. The output from Raman fiber oscillator **112** is coupled into NFM device **114** for mixing of combined wavelengths, λ_1 , λ_2 , i.e., is the difference between the Raman shifted beam and the transmitted pump beam from source **61**. As an example, high power source **61** utilizing the configuration shown in FIG. **11** (without device **62**) may have a tunable wavelength between about 1030 nm to 1090 nm and Raman fiber laser **112** will provide an output at about 1.44 μm . The resulting tunable mid-IR wavelength range is between about 3.6 nm and 4.5 nm.

In FIG. **19** polarization maintaining single mode fiber **112** is particularly employed in cases where the high power laser beam from high power pump source **61** is unpolarized or has arbitrary polarization. Such is the case for a beam produced from high power pump source **61** utilizing a double clad amplifier **69A** as illustrated in FIG. **11**. For efficient frequency mixing in a NFM device, such as device **114**, polarized light is fairly critical. In principal, double clad fibers can be polarization maintaining to provide a polarized output, as is the case in both FIGS. **16** and **19**. Fabrication of a polarization maintaining fiber typically requires a modification in the fiber cladding to achieve asymmetry in the fiber core so that there is a refractive index difference in orthogonal directions. A known example of achieving such asymmetry is called the "bow-tie" fiber. Another type of configuration would be a core that has an elliptical or other irregular shape vis a vis a circular shape. Alternatively, a simple solution for polarizing the output from a double clad fiber or other unpolarized laser source is to pass the output from the laser source through a polarizing filter. However, at least 50% of the light will be lost in such a polarizer. Moreover, changes in the input polarization will cause power or intensity fluctuations to appear in the polarized output which deteriorates rates the beam quality as applied to NFM device **114**, or other such polarized input beam required application, such as, in a xerographic printer image exposure system or in frequency converters, i.e., frequency doubling or frequency difference mixing or sum generation.

Alternative methods may be utilized to efficiently convert an unpolarized beam or an arbitrary polarized beam into an output beam having single, stable linear polarization employing Raman or Brillouin wavelength shifting in a polarization maintain single mode fiber. Thus, in the case of

the embodiment of FIG. **19**, high power pump source **61** comprises a pump laser diode source coupled to a double clad fiber amplifier doped with a rare earth such as Yb or Nd, as previously illustrated in connection with the embodiment of FIG. **11**. The output beam at wavelength, λ_1 , is provided as input to polarization maintaining, single mode fiber **112** having Bragg gratings or other reflectors **111** and **113** at the wavelength of the Raman or Brillouin gain of the fiber. Fiber oscillator **112** provides a polarized Raman or Brillouin shifted output beam. Fiber **112** without reflectors **111** and **113** will function as amplifier and can be provided in the embodiment of FIG. **11** in place of amplifier **69A**. The Raman and Brillouin amplifier or oscillator is based on conventional silica fibers and rely on the natural Raman and Brillouin gain in silica fibers. Input reflector **111** has high transmission at the pump wavelength, λ_1 , and high reflection at the Raman or Brillouin gain wavelength, λ_2 . For Raman shifting, the typical difference between pump source wavelength and Raman gain is approximately 70 nm. For Brillouin gain the wavelength shift is in the tens of GHz or sub-Angstrom range. By introducing a small amount of loss in the polarization maintaining, single mode fiber **112** for one of the directional polarizations, the fiber will operate in a single polarized mode providing a polarized output beam. This polarization dependent loss in fiber **112** can be introduced in a number of different ways, such as, by bending the fiber in one direction, reducing one side of the fiber close to the fiber core, or introducing into the body of the fiber or into the reflectors **111** and/or **113** polarization dependent loss mechanisms.

As indicated above, fiber **112** can also be operated as a Raman or Brillouin amplifier by injecting a signal source into an end of fiber **112**, as in the case of FIG. **11**. Brillouin gain is effective only in one direction, i.e., it is effective only on counter propagating beams in fiber **112** so that the signal from signal source **66A** must be injected into the reflector **113** end of fiber **112**. Raman gain is effective in both fiber directions, and the input signal may be injected into either end of fiber **112**. However, the Brillouin gain in fiber **112** is much higher than the Raman gain, at least two orders of magnitude higher. Therefore, the Brillouin amplifier will operate under cw conditions even at relatively low signal injection powers, such as several 100 mW. To be most effective, the Raman amplifier should be operated with high peak powers. Polarization maintaining silica fiber **112** can be replaced by a polarization maintaining rare earth fiber, such as disclosed and discussed in connection with FIG. **16**.

In summary, Raman or Brillouin gain in a fiber may be used to provide either an amplifier or an oscillator. In the case of the amplifier, the input beam, for example, at a wavelength of 1.06 μm , will overlap with the polarization direction of the fiber gain and provide a polarized output having wavelengths. Such a linearly polarized output would be suitable for use with a QPM DFM nonlinear device such as device **54** in FIG. **10**. However, with the use of reflectors **111** and **113**, a Raman or Brillouin oscillator is formed providing a fixed polarization output at a shifted wavelength. Such a linearly polarized output of single wavelength would be suitable for use with a QPM OPO nonlinear device such as shown in FIGS. **8** and **15**.

In using Raman or Brillouin gain in fiber **112** for providing a linearly polarized output beam to a nonlinear frequency mixing device, there may develop the problem of providing no or little gain if the input pump beam is polarized relative to one of the orthogonal polarization axis of the polarization maintaining fiber **112** whereas the Raman or Brillouin oscillation and amplification was designed

along the other orthogonal polarization axis, since Raman and Brillouin gain is polarization dependent. If the input beam has a orthogonal polarization 90° of the polarization of the Raman or Brillouin gain in the fiber, the polarization relationship will be maintained in the fiber and the input beam will not overlap with the Raman or Brillouin gain so that no gain will be experienced by the input beam. This problem is circumvented by employing polarization converter **120** shown in FIG. **20**. Pump beam at wavelength, λ_1 , is provided to fiber **112** which has reflective gratings **111** and **113** at each end of the fiber with reflectivity at the Raman wavelength of the fiber. Fiber **112** can also be employed as amplifier without gratings **111** and **113**. The produced dual wavelength output from fiber **112** is collimated by lens **125** and passed through a first wave plate **126** which changes the angle of polarization by a proscribed small amount prior to the reflection of the pump beam wavelength, λ_1 , back into fiber **112** via mirror **124**. Mirror **124** has reflectivity for the wavelength, λ_1 , of the pump beam but has low reflectivity for the wavelength, λ_2 , of the linearly polarized Raman amplified beam which is transmitted through mirror **124** to a polarization sensitive application requiring a polarized beam input for optimum performance, such as NFM device **128**.

The polarization vector of the reflected pump beam λ_1 is rotated again by wave plate **126** and reenters fiber **112** at a angular polarization direction different from the original polarization direction which, in the case of originally matching orthogonal beam polarization, will now no longer be present. The returning beam will now be subjected to the overlapping Raman or Brillouin gain of the fiber. As a result, the returning pump beam λ_1 becomes scrambled along fiber **112** providing uniform gain for any propagating polarized Raman beam within fiber **112**.

Wave plate **127** provides for return of the polarization direction of the Raman beam at wavelength, λ_2 , transmitted through mirror **124** to be converted to the proper polarization axis for the particular polarization sensitive application. As an example, wave plates **126** and **127** together must be equal to a $\frac{1}{2}\lambda$ shift to shift the polarization by 90° so that wave plate **126** may, for example, be $\frac{1}{8}\lambda$ while wave plate **127** is $\frac{3}{8}\lambda$ or $\frac{5}{8}\lambda + n\lambda$.

FIG. **21** is another polarization converter **130** operative in a manner similar to polarization converter **120** of FIG. **20** except that wave plates **126**, **127** are replaced with two short sections of polarization maintaining fibers **132**, **134** having the same functionality as wave plates **126**, **127**. Fibers **132**, **134** are spliced or otherwise optically coupled to each other at **139** and to fiber **112** at **138** to provide for efficient beam coupling and a more compact configuration. Fiber **112** has a polarizing maintenance feature or mechanism such as the bow-tie configuration shown at **135** in FIGS. **21A–21C**. The angular orientation of the feature is indicated by dotted line **136A** which corresponds to the polarization direction of the fiber gain.

Short coupled fiber **132** has a reflective device **133** formed at its forward end which may be a Bragg reflector or other fiber reflector. Reflective device **133** is reflective of the pump wavelength, λ_1 , of the pumping beam but transmits the Raman or Brillouin gain wavelength, λ_2 . However, the orientation **136A** of bow-tie configuration **135** for fiber **132** is different, as shown in FIG. **21B**, so that any polarization axis of the pump beam that is substantially orthogonal with the polarization axis of fiber **112** will be slightly rotated by the difference in angular orientation between orientations **135A** and **136B** shown in FIGS. **21A** and **21B**. As a result, such polarized input light will be subject to the gain of fiber

112. Fiber **134** functions similar to wave plate **127** in that the Raman or Brillouin output beam is changed to the original polarization orientation **136C**, shown in FIG. **21C**, designed for the particular application to which the beam is to be applied. In other words, the orthogonal relationship of proper polarization direction is maintained for the output beam, λ_2 . As an example, fiber **132** may have a $\frac{1}{8}\lambda$ shift so that fiber **134** must provide a $\frac{3}{8}\lambda$ shift to place the output beam with a proper orthogonal polarization orientation **137A**.

It will be understood by those skilled in the art that any asymmetry producing strain in the fiber in a transverse orthogonal direction of the fiber optical axis is sufficient to control beam polarization including the above mentioned bow-tie configuration. Such asymmetry causes losses to the pump beam but in the case of rare-earth doped fiber laser, the fiber core can be Er:Yb co-doped to increase amplification efficiency, or, in the case of a Raman laser, the core may be doped with Ge in high concentration to increase amplification efficiency.

Mid-IR source **140** shown in FIG. **22** is a derivation of any one of FIGS. **11**, **13** or **14** and the description relative to FIG. **11** of like components with the same numerical identification is equally applicable to source **140**. However, source **140**, in addition, includes an Er:Yb doped, single mode fiber amplifier **142** for receiving the pump beam from high power pump source **61**. Co-doped fiber amplifier **142** provides for an increase in the pumping bandwidth of the propagating beams formed in fiber **142** of wavelengths, λ_1 and λ_2 , by employing co-dopants so that the overall mid-IR bandwidth of tunable frequencies, via tuning signal source **62**, is correspondingly increased. As an example, if λ_1 is $1.06\ \mu\text{m}$, the output of amplifier will be at wavelengths $1.06\ \mu\text{m}$ and λ_2 equal to $1.55\ \mu\text{m} \pm 30\ \text{nm}$. Thus, the wavelength difference of approximately 40 nm to 50 nm between λ_1 and λ_2 , is sufficient for mixing in NFM device **64**, which in the case here is preferably a QPM DFM device. Tunable laser diode **62** can adjust the range of wavelength difference thereby further broadening the range of achievable mid-IR wavelengths that can be obtained from NFM device **64**.

An alternative modification for source **140** is the use of Bragg reflectors **144** and **145** at the ends of fiber amplifier **142** to provide an oscillator and provide a single modified output wavelength, λ_2 , for NFM device **64**, which in this case is preferably a QPM OPO device. Tunable laser diode **62** would, therefore, not be used in this alternative modification. As an example, if the wavelength, λ_1 , of output beam from source **61** is $1.06\ \mu\text{m}$, the output beam from oscillator **142** would have a wavelength, λ_2 , of about $1.55\ \mu\text{m}$. A further modification of this alternative is to employ a frequency tuning mirror, such as shown at **104** in FIG. **18**, in the location of tunable laser diode **62** so that the oscillator cavity for fiber oscillator **142** would include beam combiner **63** and the additional frequency tuning mirror. In this manner, the output wavelength, λ_2 , could be varied so that the range of possible mid-IR wavelengths from device **64** can be extended. In the case where source **61** is pulsed, a 30 watt peak power is possible where optical fiber **142** is Nd doped.

Relative to the alternative form for source **140** discussed in the previous paragraph, it should be understood that that oscillator **142** with gratings **144**, **145** may also be tunable for producing the second wavelength, λ_2 , of desired frequency so that the mid-IR range of the NFM device can be extended. This is illustrated in FIG. **24**. Mid-IR wavelength source comprises a rare-earth doped fiber oscillator or a Raman or Brillouin oscillator **161** having Bragg gratings **162G** formed

at the fiber ends to form an oscillator cavity. Oscillator 161 is pumped by high power source 61 and the period of gratings 162G are designed to produce a shifted wavelength, λ_2 , for presentation with the pump wavelength, λ_1 , to NFM device. Pump source 61 may be a fixed or tunable wavelength and oscillator 161 is tunable by means of tuning devices 162T. Tuning devices 162T may wavelength tune gratings 162G by stretching the fiber grating (U.S. Pat. No. 5,007,705 to Morey et al.); by compression of the fiber grating (U.S. Pat. No. 5,469,520 to Morey et al.); by thermal variation of the grating (U.S. Pat. No. 5,159,601 to Huber); by employing a piezoelectric transducer (U.S. Pat. No. 5,446,809 to Fritz et al.); by mechanically bending the grating fiber, or rotating the grating relative to the fiber or moving the grating relative to a side-polished region of the fiber (see patents of Sorin et al., such as U.S. Pat. No. 5,058,997); and by opto-electric effect by application of an applied electric field across the grating wherein increasing voltage of the field, such as a negative voltage, causes an increase in the refractive index only in the UV exposed regions forming the grating, shifting the grating reflectivity to longer wavelengths (T. Fujiwara et al. in the paper entitled, "UV-Excited Poling and Electrically Tunable Bragg Gratings in a Germanosilicate Fiber", Postdeadline Paper, pp. PD6-1 to PD6-5, *Optical Fiber Conference '95*, (February, 1995). The resulting effect is that the wavelength, λ_2 , can be adjusted to extend the range of possible mid-IR wavelengths generated by NFM device 164.

In of the foregoing embodiments, it should be clear that two factors are of importance in providing for efficient mid-IR frequency conversion. The first factor is that the pump and/or injection mid-IR wavelengths must be of high power in order to take advantage of the efficiency of operation of the NFM device. Otherwise, without sufficient input power provided to the NFM device, the frequency conversion will not be effectively carried out. The second factor is that of tunability of the input power is important in order to extend the possible range of mid-IR frequency conversion. Such tunable sources can be situated in various pump, injection, amplifying, or wave shifting devices employed to provide the input for the NFM device.

Although the invention has been described in conjunction with one or more preferred embodiments, it will be apparent to those skilled in the art that other alternatives, variations and modifications will be apparent in light of the foregoing description as being within the spirit and scope of the invention. Thus, the invention described herein is intended to embrace all such alternatives, variations and modifications that are within the spirit and scope of the following claims.

What is claimed is:

1. A mid-IR tunable frequency system comprising:

a first semiconductor gain source having a first tunable near-IR frequency range of about 780 nm to about 980 nm for providing a first near-IR frequency output within the first tunable range;

means to tune said first semiconductor gain source to a first near-IR frequency;

a second semiconductor gain source having a second tunable near-IR frequency range of about 1,000 nm to about 1,150 nm for providing a second near-IR frequency output within the second tunable range;

means to tune said second semiconductor gain source to a second near-IR frequency;

means for optically combining said first and second near-IR frequency outputs; and

a nonlinear frequency mixing device comprising a QPM nonlinear crystal coupled to receive said first and second combined outputs as an input and produce an output beam having an output frequency selectable within a mid-IR frequency range extending from about 2 μ m to about 5 μ m.

2. The mid-IR tunable frequency system of claim 1 further comprising means to vary the temperature of said nonlinear frequency mixing device to vary its frequency mixing response.

3. The mid-IR tunable frequency system of claim 1 wherein said nonlinear frequency mixing device provides either difference frequency mixing (DFM).

4. The mid-IR tunable frequency system of claim 3 wherein said nonlinear frequency mixing device is a nonlinear crystal device selected from the group of materials consisting of LiTaO₃, LiNbO₃, and KTP.

5. The mid-IR tunable frequency system of claim 4 wherein said nonlinear crystal device comprises a waveguide region formed in a bulk region of said crystal device for receipt of said first and second output beams, a cladding region formed over said waveguide region and having a refractive index lower than a refractive index of said formed waveguide region.

6. The mid-IR tunable frequency system of claim 1 wherein said nonlinear frequency mixing device comprises a periodic pattern of domain inversions providing a plurality of selectable periodic pattern variations,

and means to select a periodic pattern to extend the tunable extent of said mid-IR frequency range.

7. The mid-IR tunable frequency system of claim 6 wherein said pattern period is selectable from a periodic pattern of domain inversions formed in a fan-shaped configuration.

8. The mid-IR tunable frequency system of claim 6 wherein said pattern period is selectable from a periodic pattern of domain inversions by rotation of said nonlinear frequency mixing device about an axis.

9. The mid-IR tunable frequency system of claim 6 wherein said pattern period is selectable from a periodic pattern of domain inversions by lateral shifting of said nonlinear frequency mixing device relative to said first and second combined outputs, said nonlinear frequency mixing device comprising a plurality of adjacently disposed nonlinear bulk or waveguide regions parallel with first and second combined outputs at least some of which have different nonlinear pattern periods.

10. The mid-IR tunable frequency system of claim 1 wherein said semiconductor gain sources comprise two laser diode sources.

11. The mid-IR tunable frequency system of claim 1 wherein each of said semiconductor gain sources are tunable over a near-IR wavelength range greater than 10 nm having selectable near-IR wavelengths differing from one another by at least 50 nm.

12. The mid-IR tunable frequency system of claim 1 wherein said semiconductor gain sources comprise laser diode sources having their output beams coupled to a respective gain medium, said gain medium providing a beam comprising said first near-IR wavelength.

13. The mid-IR tunable frequency system of claim 12 wherein said gain medium comprises a rare-earth doped fiber amplifier, a rare-earth doped fiber laser, a Raman or Brillouin fiber amplifier, a Raman or Brillouin fiber laser, or a semiconductor amplifier.

14. The mid-IR tunable frequency system of claim 12 wherein said gain medium comprises a fiber gain medium.

15. The mid-IR tunable frequency system of claim 12 wherein in said fiber gain medium is wavelength tunable.

16. The mid-IR tunable frequency system of claim 15 wherein said fiber gain medium includes a fiber grating, said tunable wavelength achieved by stretching, compressing, bending, heating or applied electric field to said fiber grating.

17. The mid-IR tunable frequency system of claim 1 wherein a gain medium is optically coupled between said first semiconductor gain source and said nonlinear frequency mixing device to provide additional power to said input outputs.

18. The mid-IR tunable frequency system of claim 17 wherein in said gain medium comprises a rare-earth doped fiber amplifier, a rare-earth doped fiber laser, a Raman or Brillouin fiber amplifier, a Raman or Brillouin fiber laser, or a semiconductor amplifier.

19. The mid-IR tunable frequency system of claim 17 wherein in said gain medium comprises a fiber gain medium.

20. The mid-IR tunable frequency system of claim 19 wherein in said gain medium is a single mode, polarization maintaining fiber amplifier.

21. The mid-IR tunable frequency system of claim 19 wherein in said gain medium is a single mode, polarization maintaining fiber laser.

22. The mid-IR tunable frequency system of claim 19 wherein the output of said gain medium is coupled to at least one polarization maintaining fiber for polarization reorientation of said first and second outputs.

23. The mid-IR tunable frequency system of claim 19 wherein said fiber gain medium is wavelength tunable.

24. The mid-IR tunable frequency system of claim 23 wherein said gain medium includes a fiber grating, said tunable wavelength achieved by stretching, compressing, bending, heating or applied electric field to said fiber grating.

25. A mid-IR tunable frequency system comprising:

a first semiconductor gain source for providing a first near-IR frequency output;

a second semiconductor gain source for providing a second near-IR frequency output;

means to tune at least one of said semiconductor gain sources to a near-IR frequency within a range of tunable near-IR frequencies;

means for optically combining said first and second near-IR frequency outputs; and

a nonlinear frequency mixing device comprising a QPM nonlinear crystal coupled to receive said first and second combined outputs as an input, said nonlinear frequency mixing device further comprising a plurality of selectable quasi-phase matching periods; and

means to select one of said quasi-phase matching periods in combination with frequency output selection via said at least one semiconductor gain source to produce an output frequency selectable within a mid-IR frequency range extending from about 2 μm to about 5 μm .

26. The mid-IR tunable frequency system of claim 25 wherein said first semiconductor gain source is tunable within a range of about 776 nm to about 900 nm and said second semiconductor gain source is tunable within a range of about 1,000 nm to 1,100 nm.

27. The mid-IR tunable frequency system of claim 25 wherein said selection means comprises a pattern of quasi-phase matching periods formed in a fan-shaped configuration in said nonlinear frequency mixing device and means to laterally translate said nonlinear frequency mixing device relative to said combined input to select one of said quasi-phase matching periods.

28. The mid-IR tunable frequency system of claim 25 wherein said selection means comprises a plurality of different quasi-phase matching periods formed in adjacent rows in said nonlinear frequency mixing device in an axial direction of said combined input and means to laterally translate said nonlinear frequency mixing device relative to said combined input to select one of said quasi-phase matching periods.

29. The mid-IR tunable frequency system of claim 25 wherein said selection means comprises a quasi-phase matching period formed in said nonlinear frequency mixing device and means to rotate said nonlinear frequency mixing device relative to said combined input to change the quasi-phase matching period to select one of plurality of said quasi-phase matching periods achievable through its rotation.

30. The mid-IR tunable frequency system of claim 25 wherein at least one of said near-IR semiconductor gain sources comprises a tapered gain amplifier with an externally tuned cavity forming an oscillator and the other of said near-IR semiconductor gain sources comprises a DBR master oscillator coupled to a tapered gain amplifier.

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